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THE UNIVERSITY OF ALBERTA

SOIL REACTING FORCES AND ENERGY REQUIREMENT OF ROD WEEDERS

by

XUEYUAN BAI

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

EDMONTON, ALBERTA

FALL 1988

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ABSTRACT

A rod weeder experiment was conducted in a laboratory soil for the purpose of improving the implement's penetration and reducing its draft. A split-plot experimental design was used with differing soil types in the main plots and differing rod shapes, travel speeds, rod speeds and tillage depths in the sub-plots.

The data were collected by a computer based stationary six-cell dynamometer data acquisition system to measure the forces on the rod. Among the four types of rod tested; round, square, triangle and fluted rods, the fluted rod had the least draft and vertical reaction because its fluted shape and relatively smaller effective diameter lowered the plane of separation below which soil must be compacted and, in turn, reduced the compaction and used less energy.

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1. INTRODUCTION

Most of the agricultural crops grown on the central high plain of Western Canada and the bordering states in the United States are grown under semi-arid conditions, where the rainfall is the major limiting factor. The annual mean precipitation is 400 mm in Alberta, 406 mm in Saskatchewan and 504 mm in Manitoba (Bergsteinsson, 1980), therefore, water conservation is the main concern in agricultural production.

The early settlers of the last century began seeking more suitable farming methods. The practice of summerfallowing was introduced in 1889 (Pelton, 1980). It was observed that summerfallowing produced higher yield and resulted in fewer crop failures than did the continuously cropped land. Meanwhile many secondary tillage implements had been developed such as field cultivators, harrows, rod weeders *etc.*. The efforts to improve implements have continued ever since.

The rod weeder is used for secondary tillage operations for stubble mulching, moisture conservation, erosion and weed control, and seed bed preparation. According to Atkins (1979), the development of the rod weeder began in 1910. Because of the light draft and excellent weed killing, rod weeders are now widely used in regions experiencing semi-arid conditions and wind erosion such as in Western Canada, *north* western United States and other countries like Soviet Union and Australia.

In the three Canadian prairie provinces, there are approximately 17 million hectares of farm land seeded to cereal crops annually and about 10.1 million hectares summerfallowed (Anonymous, 1979). Even a small reduction in cost by reducing the draft would be a substantial total saving.

2. LITERATURE REVIEW

2.1 Tillage in General

The most obvious feature of a farming system, apart from its crops, is the system of tillage by which crops are grown. Originally, tillage was introduced to prepare a seed bed in which desirable plants of economic value could germinate and grow. It would mean anything from felling and burning a path of virgin jungle and making holes in the cleared ground with a digging stick, to creating a fine tilth and deep straight furrows in a field that has been continuously cultivated for centuries. In modern farming, "various tillage practices are used for many other reasons such as the incorperaion of crop residues and fertilizers; the management of surface trash; the control of weeds; the improvement of soil physical conditions, including moisture, aeration and temperature; the control of insect and disease problem; the control of wind and water erosion; the provision of drainage; and perhaps several others." (Pelton, 1980). The ultimate objective of tillage will always be to maximize production at a minimum cost.

2.1.1 Evolution of tillage practice

Tillage practices have been developed over thousands of years ever since the beginning of the Neolithic revolution. Carbon-11 dates have proven that Chinese started growing millet and rice in the neolithic village of the Wei River

valley and the Yangtze Delta in about 5000 B.C. (Needham, 1984). At the early stage, the tillage tools were nothing more than polished axes, straight sickles, hoes or daze, made from either igneous rock or flint, and sharpened sticks.

With the development of iron casting, iron implements were introduced. The earliest iron hoes and spades found in China so far date from the late Spring and Autumn period (770 B.C. to 470 B.C.). By the Warring States period (475 B.C. to 221 B.C.), iron ploughshares were found in sites all over China (Needham, 1984). These ploughs and improved models served as the major tillage tools for centuries until the late 1700's, when the mould-board plough was introduced from Europe (Needham, 1984).

As a result of the industrial revolution, the evolution of tillage practices has progressed considerably. Tractors and many new equipment were introduced. All of these factors makes it possible to feed the ever growing population in the world.

2.1.2 Tillage practices

Conventional tillage, minimum tillage and zero tillage are the three most commonly used tillage practices in North America. Conventional tillage usually refers to the complete inversion or through mixing of the top soil as a primary operation followed by one or more secondary operations to incorporate fertilizers and herbicides (or otherwise kill

weeds) and to firm the seed bed, the seeding operation itself and perhaps post-emergent cultivation.

Conventional tillage practices can achieve total weed control and provide an excellent seed bed, however, they utilize a multiplicity of operations, sometimes in excess of need. They destroy the protective cover of the soil surface thus exposing it to the forces of wind and water, and the numerous operations become increasingly more expensive in terms of time, fuel and equipment costs.

In minimum tillage practices, the number of tillage operations along with the herbicide application are reduced to a minimum required for weed control, seed bed preparation, moisture conservation and trash conservation. Minimum tillage practices are mainly used in semi-arid regions where water conservation and wind erosion are the major concerns.

Zero tillage approaches the ultimate in the minimum tillage system. It refers to a crop production system in which the seed is planted in a seed bed that has not been tilled since the harvest of the preceding crops and where weeds, diseases and the pests are controlled solely by chemicals. Since fewer field operations are required, fuel and time are saved and at the same time the soil is also protected against water and wind erosion by plant residues. However, zero tillage does not necessarily increase the yield and the cost of chemicals and the side effects of chemicals also limit the zero tillage practice.

2.1.3 Tillage in western Canada

Under the semiarid climatic conditions in western Canada, the farmers' main concern has always been water conservation and erosion control. Summerfallowing has been widely practiced as a means of conserving moisture in the soil profile for the use by a subsequent crop since the late 1930's. With the development of the chemical industry, more effective fertilizers, herbicides and pesticides have been put into use, and thus minimum and tillage practices become possible. Minimum and zero tillage practices have increased during the last two decades as a consequence.

There is a wide range of tillage equipment that will control weeds and prepare the seed bed while leaving a substantial amount of crop residue on the soil to protect against wind and water erosion. The choice of an implement or a combination of implements will not only depend on the specific task to be accomplished but also on the soil type and climatic conditions. Moreover, power, fuel, and time requirements are other important considerations. Pelton (1980) suggested that in western Canada, before a farmer makes a decision, he must ensure that he can:

1. place seed in firm contact with moist, fertile soil;
2. protect his land from wind and water erosion;
3. provide adequate weed control; and
4. utilize available moisture efficiently and effectively.

2.2 Tillage Mechanism

Tillage is defined by Gill and Vanden Berg (1967) as mechanical manipulation of the soil. For a tillage tool to manipulate the soil effectively, the soil must either deform or fail. The soil behavior in tillage is a complex process as noted below.

2.2.1 Soil characteristics

An agricultural soil is a porous mixture of inorganic particles, decaying organic matter, air and water (Buckman and Brady, 1969). It is a heterogeneous, nonlinear, nonconservative, and anistropic material, due respectively to its variability, stress-strain relationship, its ability of "remembering" changes which have occurred in the past and its differences in behavior along different directions (Holtz and Kovacs, 1981).

In agricultural engineering, soil mechanics and dynamic are used to design tillage tools, to study soil vehicle interaction, and to analyse the performance of farming machinery. Koolen and Kuipers (1983) generalized that the forces applied to soil in farming operations generally had a short duration, a small loaded area, and small intensity in comparison with the forces occurring in soil mechanics problems in civil engineering.

Soil texture refers to the proportion of material of each grain size present in a given soil (Procedures for Testing Soil, 1969). The textures of agricultural soil vary

from sand to soils with very high percentage of clay and/or organic matter content. Soil texture is one of the most important properties of soil and is basic to an agricultural soil classification. Sand, loam and clay are the three fundamental groups of soil. Texture of soil with other factors like moisture content may greatly affect soil dynamic properties.

The soil classification for engineering purposes is primarily based on the grain size distribution. On the basis of the three groups of soil (sand, silt and clay) additional class names have been devised. A more accurate and fundamental method for an agricultural soil classification has been established by the United States Department of Agriculture (Buckman and Brady, 1969).

Agricultural soils generally exhibit both plastic and elastic behavior. With the application of stresses on soil; shear, compression and tension will occur. Their behavior in nature is some combined action and the extent of each depends on the soil conditions. However, compression and shear are most commonly found in tillage.

2.2.2 The Mohr-Coulomb failure criterion

Failure in soil is much more complex than in most brittle materials. There are many ways to define soil failure, among which the most commonly used one is the Mohr-Coulomb failure criteria (Holtz and Kovacs, 1981).

Figure 2.1 The Mohr-Coulomb strength equation presented graphically (reformed from Holtz, 1981)

According to Holtz and Kovacs (1981) Mohr hypothesized a criterion of failure for materials in which he stated that they fail when the shear stress on the failure plane reaches some unique function of the normal stress. Also according Holtz and Kovacs, Coulomb had studied the shearing strength of soil. He had observed that there was a stress-dependent component of shear strength, the angle of internal friction, and a stress-independent component named as the intrinsic cohesion. The combination of the two approaches gave birth to the Mohr-Coulomb failure criterion, which can be written as:

$$\tau_s = \sigma_s \tan\phi + C \qquad (2.1)$$

where τ_s = shear strength of the soil (kPa),

σ = applied normal stress (kPa),

ϕ = angle of internal friction (deg.), and

C = cohesion of the soil (kPa).

It describes the maximum stress within the failure plane and not the stress beyond it. Equation 2.1 can be graphically presented as a straight line as shown in Figure 2.1. C and ϕ in equation 2.1 are called the soil strength parameters. Gill and Vanden Berg (1967) stated that they were only parameters of the assumed yield equation and their logical existence can be explained by an interpretation of the equation and not from the physical nature of the soil itself.

The Mohr-Coulomb failure criterion, because of its simplicity, is widely used in practice, although it is by no means the only possible failure criterion for soil. The failure envelope for a particular soil may not necessarily be a straight line, but a straight line approximation can be taken over the stress range of interest and the shear strength parameters determined for that range (Craig, 1980).

2.2.3 Soil-tool mechanics

The fundamental characteristic for a simple tillage tool, *e.g.* inclined plane, moving through the soil along a straight path at a slow speed (Figure 2.2), according to Soehne (1956), is a repeated failure of the soil by shear, forming small blocks of soil. He analyzed the action of a simplified tool and concluded that four simple behavior

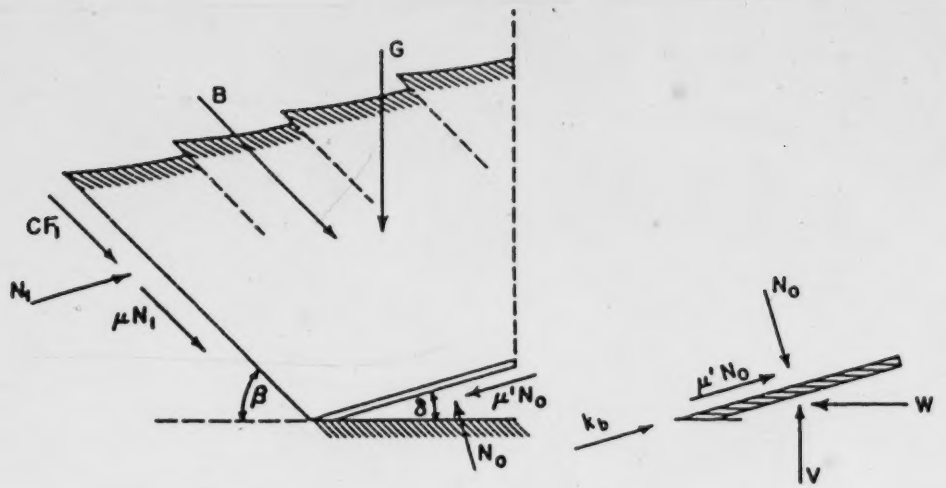

Figure 2.2 Hypothetical forces and their orientation on a segment of soil reacting to an inclined-plane tillage tool (Soehne, according to Gill and Vanden Berg, 1978)

equations described the tillage action: soil-metal friction, shear failure, acceleration force for each block of soil, and cutting resistance. Figure 2.2 shows the hypothetical forces that act on the segment of soil as it reacts to the advanced tool. Forces CF_1 and μN_1 are due to soil shear at incipient shear failure. Forces due to soil-metal friction ($\mu' N_o$) and acceleration (B) are also present. Rowe (1959) and Barnes (1961) incorporated into the mechanics the influence of adhesion on the soil metal sliding surface and derived the following equations:

$$W = \frac{G}{z} + \frac{CF_1 + B}{z(\sin\beta + \mu\cos\beta)} + \frac{C_m F_o}{z(\sin\delta + \mu'\cos\delta)} + kb \qquad (2.2)$$

$$G = \gamma bd'\left(L_o + \frac{L_1 + L_2}{2}\right) \tag{2.3}$$

$$B = \frac{\gamma}{g} bdv_o^2 \frac{\sin\delta}{\sin(\delta + \beta)} \tag{2.4}$$

$$z = \left[\frac{\cos\delta - \mu'\sin\delta}{\sin\delta + \mu'\cos\delta} + \frac{\cos\beta - \mu\sin\beta}{\sin\beta + \mu\cos\beta} \right] \tag{2.5}$$

where W = draft force (N),

G = weight of the soil segment (N),

F_1 = area of the forward shear failure surface (m^2),

F_2 = area of the inclined tool (m^2),

C = cohesion of soil (Nm^{-2}),

C_m = soil-metal adhesion (Nm^{-2}),

δ = lift angle of the tool (deg.),

μ = $\tan\phi$ coefficient of internal soil friction,

ϕ = internal friction angle of soil (deg.),

μ' = coefficient of soil-metal friction,

β = angle of forward failure surface (deg.),

γ = wet bulk density (Nm^{-3}),

k = pure cutting resistance of soil (Nm^{-1}),

b = width of the tool (m),

$d' = d\frac{\sin(\delta + \beta)}{\sin\beta}$,

d = depth of soil disturbed (m),

L_o = length of the tool (m),

$L_1 = d\frac{\cos(\delta + \beta)}{\sin\beta}$,

$L_2 = d'\tan\delta$,

v_o = velocity of the tool (ms^{-1}), and

g = acceleration of gravity (9.81 ms^{-2}).

The mechanics are not precise since many factors have not been included in the equations, such as the edge and the supporting standard effects, the presence of stone and roots *etc.*, however, the equations are adequate to interpret the tillage action.

2.2.4 Studies of rod weeders

The soil mechanics for a rod weeder is not as simple as the inclined plane, because it involves considerable soil compaction as well. Harrison and Atkins (1980) studied rod weeders and found that the draft and vertical reaction of a rod were affected by a small wedge of soil which formed in front of the rod. In order for a rod to achieve a passageway through the soil, the soil particles must be displaced vertically with some passing over and some under the tool. The soil which passed under the rod, unlike that which passes over the rod, must be compacted. Considerable compaction must occur if the plane of separation is much above the bottom of the rod, which in turn will cause added draft and a large vertical reaction upwards. The dynamics of the soil passed over the rod will likely be the same as those of a simple tool described early.

Fedorov (1970) states that the location of the separation plane can be determined by the following equation:

$$h = r \sin\phi \qquad (2.6)$$

where h = location of the plane below the rod axis (m),

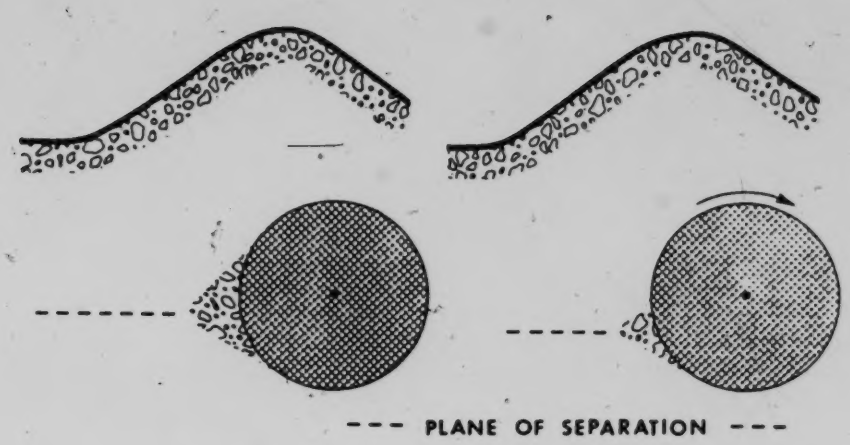

Figure 2.3 Soil wedge and the plane of separation for rotating and non-rotating rod (adapted from Harrison, 1981)

r = the rod radius (m), and

ϕ = angle of internal friction (deg.).

Equation 2.6 can be reformed as:

$$e = r (1 - \sin\phi) \qquad (2.7)$$

where e = r - h, which is the location of the plane above the bottom of the rod.

Equation 2.7 shows that the depth of the soil to be compacted below a rod is affected by two factors, the rod radius and the angle of internal friction.

In a field test, Harrison and Atkins (1981) observed that the round rod (22.2 mm in diameter) had a greater draft with the potential for poor penetration than did a square rod (22.2 mm by 22.2 mm). A minimum draft and vertical

reaction were also found at a much higher rod speed than those used in commercial rod weeders. They attributed the reduction to the higher rod speed reducing the size of soil wedge ahead of the rod and lowering the plane of separation.

The advantage of the square rod according to Harrison and Atkins (1981) is that it does not scour or self-clean like the round one. And consequently the interface friction is the internal friction of soil rather than the soil-metal or external friction of the round rod. Because the internal friction of soil is greater than the external, the soil wedge ahead of the rod is reduced and so are the vertical reaction and draft. In a personal communication, Dr. H. P. Harrison proposed that fluted and triangle rod would parallel the performance of a square rod but the edges would not wear as repidly as the square rod.

Vervein and Gaifullin (1979) obtained an opposite result in a similar study. They observed less draft for a 25 mm diameter round rod weeder cultivator than for a 25 mm by 25 mm square rod in their study. They observed that the draft of rod weeder is proportional to the effective diameter of the rod. Figure 2.4 is based on the data obtained by Vervein and Gaifullin (1979). The differences between the results of Harrison and Atkins (1981) and Vervein and Gaifullin's studies could be attributed to differences in a number of factors, such as soil type, ground speed, and/or rod rotating speed.

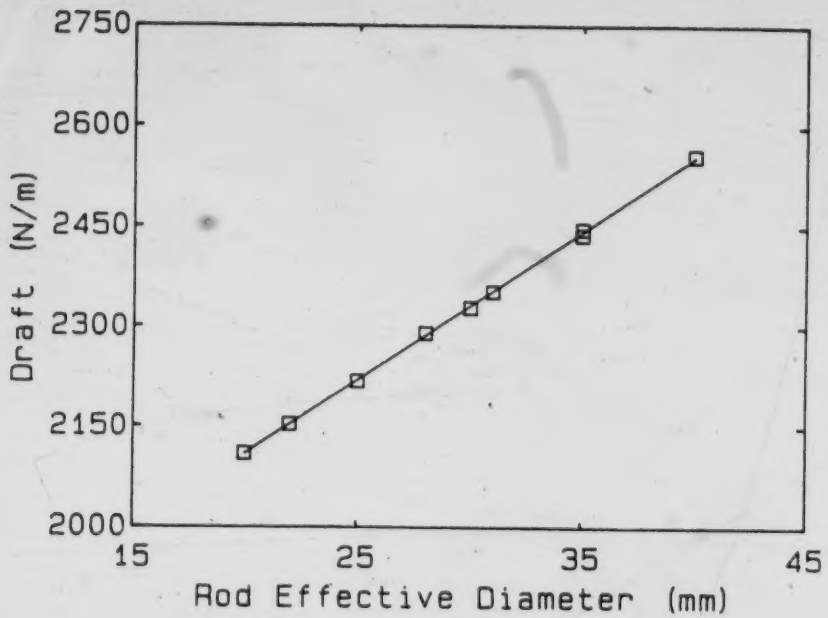

Figure 2.4 Relation between the draft of rod weeder and the effective diameter of rod (data from Vervein and Gaifullin, 1979)

Kotov (1979) studied the influence of adding shoes and sweeps to the standards of rod weeder cultivators when the attachments were placed at the height of the rod. He found that the draft was significantly decreased and the direction of the vertical reaction was not directed upward, as was observed for the conventional rod weeders, but downward which facilitated the penetration of the rod.

2.3 Summary and Objectives

Tillage practices dependent on technology and local climatic conditions. In semiarid regions, tillage practices reqire implements that aid erosion control and water conservation.

By understanding the soil-tool relationship, better farming implements can be developed to improve tillage efficiency and minimize the cost. Many tillage implements have been developed in western Canada to meet the needs of dry land farming. The Rod weeder is one of the commonly used for secondary tillage.

One of the problems associated with rod weeder is its poor penetrability, therefore the studies on rod weeders should consentrate on improving its penetration. The general objective of this study was to design rods improving the penetration and reducing draft.

The specific experimental objectives of this study were:

1. to determine the soil reacting forces and energy requirements on the fluted and triangle rod in comparison with the conventional rods;
2. to determine the relationship between the soil reacting forces and the rod rotating speed; and
3. to determine the effects of soil type, tillage depth and travel speed on the soil reacting forces.

3. EXPERIMENTAL MATERIALS, DESIGN AND PROCEDURE

3.1 Factors and Their Levels

According to the objectives of this study, five variables or factors and their levels were chosen (Table 3.1).

3.1.1 Soil types

Two types of soil, loam and sand, were used in this experiment. The loam soil, which consisted of 26.1 % clay, 39.6 % silt and 33.6 % sand (Maule, 1984), was obtained from the Ellerslie Research Station of the University of Alberta near Edmonton. Except for screening off roots and leaves there was no treatment of the soil. The sand used was grade Sil-4 commercial construction sand. Figure 3.1 shows the grain size distribution of the sand. Pure sand, which is cohesionless, was chosen to determine the effects of cohesion on the draft and vertical reaction forces.

3.1.2 Rod shapes

The four types of rods used in the experiment were: fluted, triangle, round and square. The first two were included in the study to see what advantage they would have over the conventional ones. As discussed earlier, the triangle rod and the fluted rod are supposed to have lower vertical reaction and draft. Round and square rods were the conventional rods commonly used in western Canada. By using

Table 3.1 FACTORS AND THEIR LEVELS

Factor	Symbols	Level
Soil Type	T1	Loam
	T2	Sand
Rod Shape	S1	Fluted
	S2	Triangle
	S3	Round
	S4	Square
Travel Speed	V1	0.39 m/s
	V2	0.66 m/s
Rod Speed	R1	30 rpm
	R2	100 rpm
	R3	170 rpm
	R4	240 rpm
	R5	310 rpm
Depth	D1	50 mm
	D2	80 mm

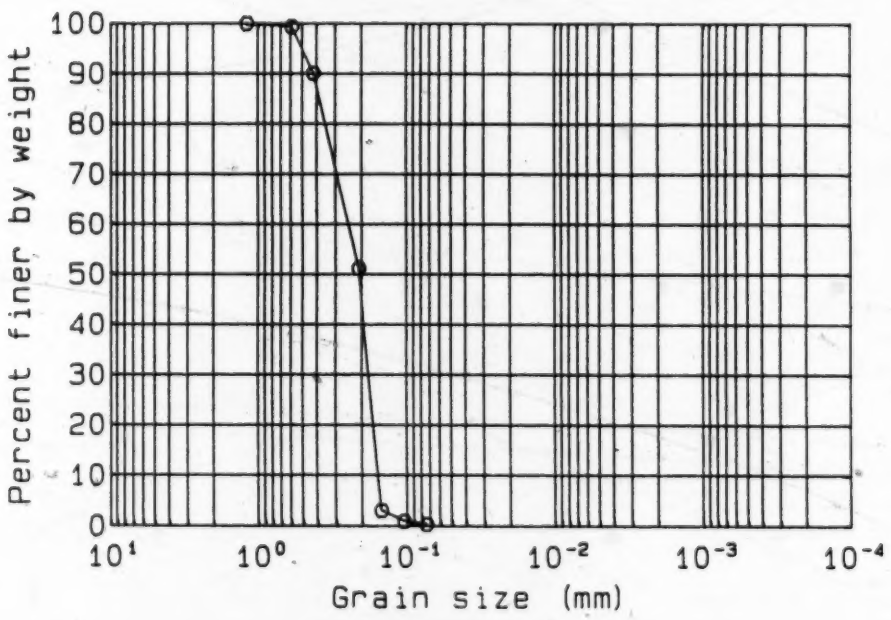

Figure 3.1 The grain size distribution of sand

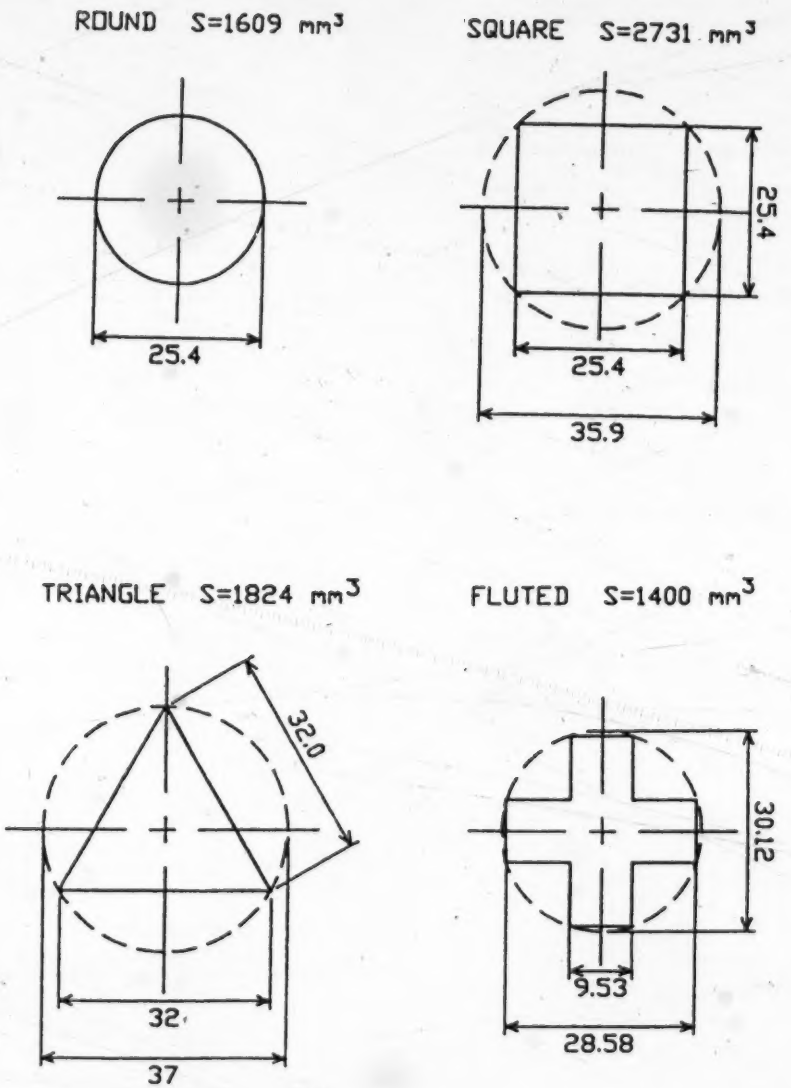

Figure 3.2 The geometric shapes, sizes (mm) and section moduli (S) of the rods used in the experiment

rods that included both round and square rods, the differences that occured between Harrison and Atkins (1981) and Vervein and Gaifullin's (1979) studies might be explained as discussed in Chapter 3.

The dimensions of the fluted and triangle rods were limited by two major criteria: namely, the section modulus should differ little from the conventional 25.4 mm diameter round rod so that the rod between the two stands will not be overstressed, and, the outside dimension should not exceed 36 mm as this was the effective diameter of the conventional 25.4 mm by 25.4 mm square rod because a larger effective diameter will generally result in a larger draft. The fluted rod had a overall dimension of 28.6 mm with an effective diameter of 30.1 mm and the side of the equilateral triangle rod was 32 mm with an effective diameter of 37 mm. The geometric shapes, sizes and section moduli of the fluted and the triangle rods as well as the conventional round and square rods and are shown in Figure 3.1. The section modulus for the fluted rod and the triangle rod were 1400 mm^3 and 1820 mm^3, respectively.

3.1.3 Travel speed and rod speed

Equations 2.2 and 2.4 state that the draft of a tillage tool is the function of the square of the ground speed. There are only 3 different travel speeds available in the laboratory. The lowest travel speed (0.39 m/s) and the highest travel speed (0.66 m/s) were used to determine if

the draft would increase when the ground speed increased.

Five levels of rod speed ranging from 30 rpm to 310 rpm were chosen in the experiment to determine the relationship between the draft and vertical reaction and rod speed. The rod speed range exceed that used by Atkins (1979).

3.1.4 Depth

According to equations 2.2 and 2.3, draft is a function of depth. In Atkins' study (1979), the effects for depth were not significant. After re-examining his study, it was noted that the rods used were short and possibly the experimental errors could be greater than the differences between the two depths. It was also difficult to control the depth in field conditions. Therefore, depth was chosen as a factor in this study to see if the draft would increase as the depth increased. Two depths were chosen in the range of depths commonly used in practice. A depth of 50 mm represents a typical seedbed preparation depth and a depth of 80 mm represents a typical weed control depth of rod weeders.

3.2 Equipment and Facilities

The experiment was conducted in the soil bin laboratory of the Department of Agricultural Engineering. Figures 3.2 and 3.3 shows the test unit which include a stationary six-cell dynamometer, a moving soil bin test cart, rod weeder and its power system attached to the active frame of

Figure 3.3 The stationary six-cell dynamometer and the soil-bin cart

Figure 3.4 The signal conditioner and the computer data acquisition system

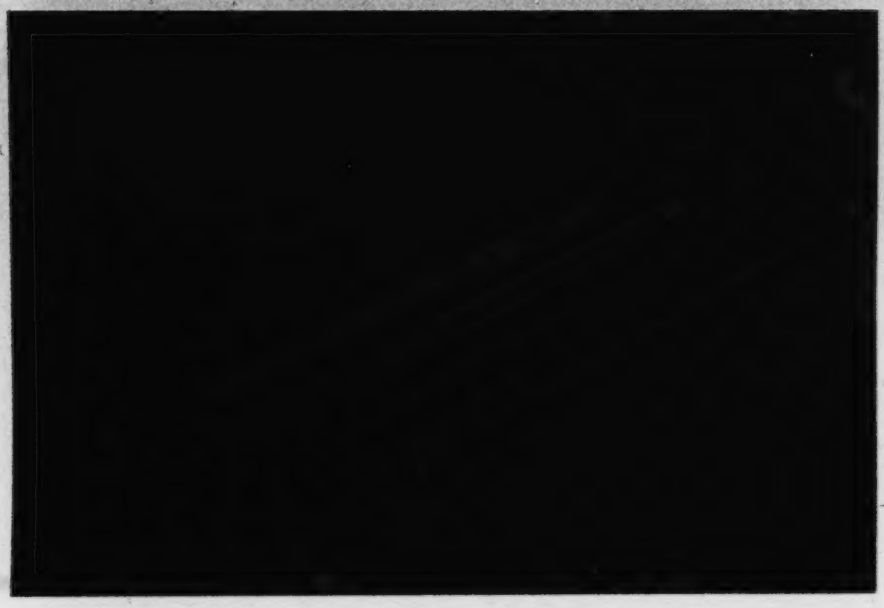

Figure 3.5 The four experimental rods

Figure 3.6 The large drive sprocket for higher rod speeds

the six-cell dynamometer, a signal conditioner, an amplifier and a computer data acquisition system.

The rods and frame were fabricated in the machine shop in the Department of Agricultural Engineering. Figure 3.4 shows the four types of rod tested. Because of the size limitation of the soil bin cart in the laboratory, the effective length of the rods was 730 mm, which did not include the boots and shanks. Every rod had a drive end and a free end which were separately made and then welded on the rod to fit in the ball bearings on the vertical stands. All rods and the frame were made of mild steel.

A speed controllable DC motor with a chain and sprocket drive was used. A large drive sprocket was used to obtain the higher rod speeds of 240 rpm and 310 rpm (Figure 3.5) whereas a small sprocket was used to get the lower rod speeds of 30, 100 and 170 rpm.

Two discs were mounted on the passive frame of the six-cell dynamometer to cut the soil to a uniform width prior to the passage of the rod, thereby minimizing soil reactions on the stands being measured along with the rod.

The rod weeder was attached on the active frame which was isolated from the passive frame by six load cells. The analog signals from the load cells were transmitted to the signal conditioner and amplified by the pre-amplifier. Since the output signals were not large enough, they were re-amplified by an analog amplifier. An IBM-PC computer with a data acquisition expansion board converted the amplified

analog signals into digital signals and then recorded them on floppy discs (Licsko and Harrison, 1986).

Other equipment and facilities used were: a gamma-ray density probe for measuring soil density, a digital stroboscope for measuring rod speed, soil analysis laboratory for analyzing the sand grain size distribution and the computer facilities for data processing and thesis preparation.

3.3 Experimental Design

Because there was only one type of soil that could be tested in the soil bin at a time, the most suitable experimental design for this study was a split plot, in which the soil types were the main plots (Steel and Torrie, 1980). Three necessary replicates in the experiment were conducted to statistically validate the results (McKibben and Berry, 1952). The soil types with their replicates in the test were in a random order. The eighty combinations of the other factors, Soil Type (T1 and T2), Rod Shape (S1, S2, S3 and S4), Rod Speed (R1, R2, R3, R4 AND R5), Travel Speed (V1 and V2) and Depth (D1 and D2), were completely randomized within each sub-plot.

3.4 Test Procedure

The soil had to be exchanged for different replications follwing a random order. After changing the soil, it was moistened and left for a few days for the soil to reach its

Table 3.2 LOAM MOISTURE CONTENT AND BULK DENSITY

Working Day	Moisture Content (%) (dry basis)	Bulk Density(kg/m³) (dry basis)
1	28.3	1046
2	26.3	1094
3	27.5	1065
4	26.7	1108
5	28.8	1080
6	24.8	1053
7	24.6	1051
8	25.4	1041
9	27.4	1007
10	25.2	1054
11	24.0	1086
12	24.2	1058
13	24.2	1069
14	24.9	1059
15	24.4	1069
16	24.2	1098
Average:	25.6	1065
σ_n^2	2.1	583

Table 3.3 SAND MOISTURE CONTENT AND BULK DENSITY

Working Day	Moisture Content (%) (dry basis)	Bulk Density (kg/m³) (dry basis)
1	2.0	1514
2	2.2	1533
3	2.0	1552
4	2.2	1549
5	2.0	1551
6	2.4	1540
7	2.4	1552
8	2.4	1545
9	2.2	1516
10	2.2	1534
11	2.3	1540
Average:	2.2	1539
σ_n^2	0.02	167

moisture equilibrium the test being conducted. The moisture content for the loam soil was approximately 26% (dry basis) (Table 3.2) and 2.2% (dry basis) for sand (Table 3.3).

Since each replicate included eighty tests, one replication took three to four days to complete. At the end of each working day, the test soil was re-moistened and tilled to the desired moisture content to minimize the variability of moisture content. The soil was tilled by a rotary tiller (Figure 3.6) and compacted by a roller (Figure 3.7) for a total depth of 40 mm.

The data for each test were sampled at the rate of 500 samples per second for five seconds. The soil moisture content and bulk density were measured with a gamma-ray transmission equipment at the middle of each working day.

Figure 3.7 The rotary tiller

Figure 3.8 The compact roller

3.5 Data Processing

After the completion of the test, the load spectrum recorded from the six-cell dynamometer were processed into two force spectra (draft and vertical reaction spectra) and one torque spectrum of the rod. Means of the draft, vertical reaction and the rotating torque were then calculated from the spectra and transferred from the random order of the experiment to a required order for the analysis of variance. Upon the determination of the significant main effects and interactions, the results were then tabulated or plotted.

4. RESULTS AND DISCUSSION

4.1 Analysis of Variance

The analyses of the variance of draft and vertical reaction are given in tables 5.1 and 5.2. For each main effect and interaction a F-ratio was carried out. All of the mean square values and the resulting F-ratio are listed in the tables and the significant levels are also indicated in the tables. Since torque varies little (22% and less) and since only about 6% of the the total power was required to rotate the rod, the analysis of variance of torque was not conducted.

The error term 1, which is the interaction of block (replicates) and soil type, is used in calculating the F-ratio for block and soil type. The error term 2, which is the sum of all the rest of interactions with block, is used in calculating the F-ratio for all the remaining sources of variance (Steel and Torrie, 1980).

Table 4.1 and 5.2 show that all of the main effects: soil type, tillage depth, travel speed, rod shape and rod speed have a significant effect on the draft and the vertical reaction at 0.5% probability level and some of their interactions have significant effects at 0.5%, 1% and 5% probability levels.

Table 4.1 ANALYSIS OF VARIANCE OF DRAFT

Source of Variation	df	Mean Square	F
Blocks (B)	2	4180.81	
Soil Type (T)	1	11633047.89	640.76 ***
BT (Error 1)	2	18155.13	
Rod Shape (S)	3	55723.11	29.84 ***
Rod Speed (R)	4	568015.61	304.14 ***
Depth (D)	1	1214929.15	650.52 ***
Travel Speed (V)	1	691928.07	370.48 ***
TS	3	23988.65	12.84 ***
TR	4	49329.59	26.41 ***
TD	1	4966.60	2.66
TV	1	30077.79	16.10 ***
SR	12	3391.32	1.82 *
SD	3	3341.99	1.79
SV	3	6472.35	3.46 *
RD	4	11147.22	5.97 ***
RV	4	14870.94	7.96 ***
DV	1	934.52	0.50
TSR	12	764.93	0.41
TSD	3	4011.65	2.15
TSV	3	2040.01	1.09
TRD	4	1511.23	0.81
TRV	4	2648.22	1.42
TDV	1	8047.08	4.31 *
SRD	12	1148.46	0.61
SRV	12	1025.37	0.55
SDV	3	1725.56	0.92
RDV	4	280.95	0.15
TSRD	12	637.91	0.34
TSRV	12	1292.28	0.69
TSDV	3	985.25	0.53
TRDV	4	359.47	0.19
SRDV	12	656.16	0.35
TSRDV	12	909.11	0.49
ERROR 2	316	1867.63	
Total	479		

* Significant to the 5% probability level
** Significant to the 1% probability level
*** Significant to the 0.5% probability level

Table 4.2 ANALYSIS OF VARIANCE OF VERTICAL REACTION

Source of Variation	df	Mean Square	F	
Blocks (B)	2	825.06		
Soil Type (T)	1	3266716.21	1897.93	***
BT (Error 1)	2	1721.20		
Rod Shape (S)	3	15751.73	37.35	***
Rod Speed (R)	4	172439.83	408.94	***
Depth (D)	1	8003.50	18.98	***
Travel Speed (V)	1	39830.74	94.46	***
TS	3	10761.01	25.52	***
TR	4	71727.10	170.10	***
TD	1	13613.26	32.28	***
TV	1	688.80	1.63	
SR	12	1064.01	2.52	***
SD	3	655.45	1.55	
SV	3	1730.48	4.10	**
RD	4	500.64	1.19	
RV	4	874.14	2.07	
DV	1	389.63	0.92	
TSR	12	452.28	1.07	
TSD	3	906.79	2.15	
TSV	3	824.25	1.95	
TRD	4	221.79	0.53	
TRV	4	172.94	0.41	
TDV	1	1096.38	2.60	
SRV	12	315.16	0.75	
SRD	12	184.62	0.44	
SDV	3	201.02	0.48	
RDV	4	108.05	0.26	
TSRD	12	228.70	0.54	
TSRV	12	239.56	0.57	
TSDV	3	217.87	0.52	
TRDV	4	50.96	0.12	
SRDV	12	281.34	0.67	
TSRDV	12	290.19	0.69	
ERROR 2	316	421.68		
Total	479			

* Significant to the 5% probability level
** Significant to the 1% probability level
*** Significant to the 0.5% probability level

4.1.1 Main effects - soil type

Tables 4.1 and 4.2 show that the soil type affects both the draft and the vertical reaction. The means of draft and vertical reaction for loam are 577 N/m and 155 N/m respectively (Table 4.3), whereas, they are only 266 N/m and -10 N/m respectively for sand. The negative vertical reaction means the force is downwards to assist the penetration of rod. The higher draft and vertical reaction in loam is largely attributed to its clay content which affects the cohesion and internal friction. Soils with clay content are cohesive whereas sand is cohesionless. The negative vertical reaction in sand indicates that the plane of separation is at or near the bottom of the rod. In general, the higher the clay content in a soil, the higher its cohesion value and the higher its shear strength as indicated in equation 2.1.

There are several interactions associated with the soil type which are noted in a subsequent section.

4.1.2 Main effects - rod shape

The rod shape has a highly significant effect on both draft and vertical reaction. If we take the mean value of the round rod (410 N/m) as 100%, then the draft for square, triangle and fluted rods are 108%, 106% and 97%, respectively, of the draft for round rod (Table 4.3).

The vertical reaction for square, triangle and fluted rods are 89%, 88% and 68%, respectively, of the vertical

Table 4.3 THE MAIN EFFECTS FOR THE DRAFT AND THE VERTICAL REACTION

Factor	Level	Draft (N/m)	Vertical Reaction (N/m)
Block	1	420	71
	2	428	72
	3	419	75
Soil Type	Loam	577	155
	Sand	266	-10
Rod Shape	Round	410	85
	Square	423	75
	Triangle	437	75
	Fluted	397	57
Rod Speed (rpm)	30	543	146
	100	452	73
	170	386	52
	240	373	50
	310	355	43
Depth (cm)	5	372	77
	8	472	69
Travel Speed (m/s)	0.39	384	64
	0.66	460	82

reaction for the round rod (57 N/m) (Table 4.3). The fluted rod had the least vertical reaction and the round one had the largest.

The soil dynamics for rod weeder, as described earlier, is a combined action of shearing and compacting. The soil which passes over the rod fails in shear whereas the soil which passes under the rod is compacted. Depending on the soil, the force to compact it can be large. The net effect can be stated by considering the two forces as the soil reaction forces S and T in Figure 4.1. The draft (L) and vertical reaction (V) can be written:

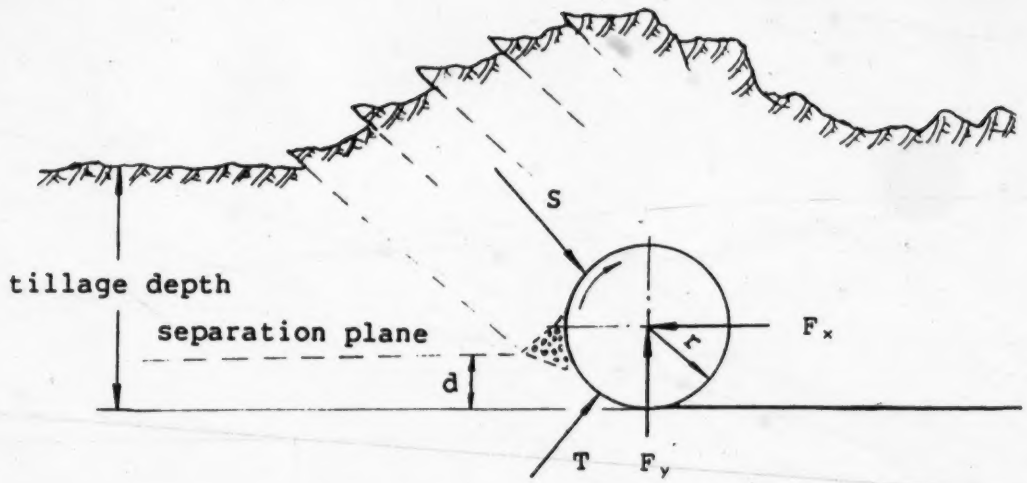

Figure 4.1 Simplified diagram of soil reaction forces acting on rod

Figure 4.2 Soil adhering to the square rod

Figure 4.3 Soil adhering to the triangle rod

Figure 4.4 Soil adhering to the fluted rod

$$L = -F_x \quad (4.1)$$

$$V = -F_y \quad (4.1)$$

$$F_x = T_x + S_x \quad (4.3)$$

$$F_y = T_y - S_y \quad (4.4)$$

where F_x and F_y are the horizontal and vertical components rod reaction;

S_x and S_y are the horizontal and vertical components of S; and

T_x and T_y are the horizontal and vertical components of T.

The dynamics of soil above the plane of separation is similar to that given in Figure 2.2, consequently, S is a function of tillage depth, cohesion *etc.*. T, on the other hand, is a function of the volume of soil being compacted.

For square, triangle and fluted rods, because the soil rotates with the rod the frictional angle is equal to the internal friction of soil. For a loam only the round rod scours or selfs clean; other rods do not (Figures 4.2, 4.3 and 4.4). Since the angle of internal friction of soil is greater than the angle of external friction of soil to metal of the round rod, the soil wedge will be altered and the plane of separation will be lowered (Harrison, 1980). From equation 2.7, the height of the separation plane for square, triangle and fluted rod would be lower than that of the round rod, provided that they all had the same effective diameter. This would result in a smaller force T and greater force S, consequently a smaller vertical reaction V. The

round rod has the highest vertical reaction even though it has the smallest effective diameter (Table 4.3); thus substantiating the observation of Harrison and Atkins (1981).

The height of the plane of separation of the square, triangle and fluted rods are not the same. Equation 2.7, $e = r (1 - \sin\phi)$, specifies that the height of the plane of separation (e) is affected by two factors: the rod radius (r) and the angle of internal friction (ϕ). For the same frictional angle (ϕ), the larger the effective diameters of the square rod and the triangle rod result in large values of e and would account for their vertical reaction being larger than the fluted rod.

The effects on draft, however, are more complicated. On one hand, the lower separation plane would reduce the force T. On the other hand, the larger effective diameter would increase the force S, that is, the lower vertical reactions of square and triangle rod do not necessarily result in lower draft. The low draft and vertical reaction of the fluted rod are most likely due a combination of its shape and relatively small effective diameter.

Vervein and Gaifullin's results (1979) differing from Harrison and Atkins's (1981) could be due to the different soil types they used. Vervein and Gaifullin used a soil which was described as "of sandy mechanical composition", whereas Harrison and Atkins used a loam in their study. In this study, a loam also is used. Althoughin loam the draft

is not proportional to the effective diameter of the rod, in sand the draft does exhibit linearunction to the effective diameter. The effective diameters for round, square, triangle and fluted rods are 25.4 mm, 36 mm, 37 mm and 30.1 mm. The drafts for sand are 246 N/m, 289 N/m, 269 N/m and 261 N/m for round, square, triangle and fluted rods, respectively.

4.1.3 Main effects - rod speed

As the rod speed increased from 30 rpm to 310 rpm, the draft and vertical reaction reduced by 35% and 70% respectively, because the higher peripheral velocity, which is determined by the rod speed, would reduce the size of soil wedge ahead of rod and thereby lower the plane of separation (Harrison and Atkins, 1981).

Figure 4.5 shows the relationship between draft and rod speed, and the relationship between vertical reaction and rod speed. When the rod speed increased from 30 rpm to 170 rpm, both draft and vertical reaction decreased substantially, but beyond that, very little decrease occured.

The rod speed has several significant interactions which are described in the next section.

4.1.4 Main effects - tillage depth

As the tillage depth increased from 5 cm to 8 cm, the draft increased 20%, however, the vertical reaction

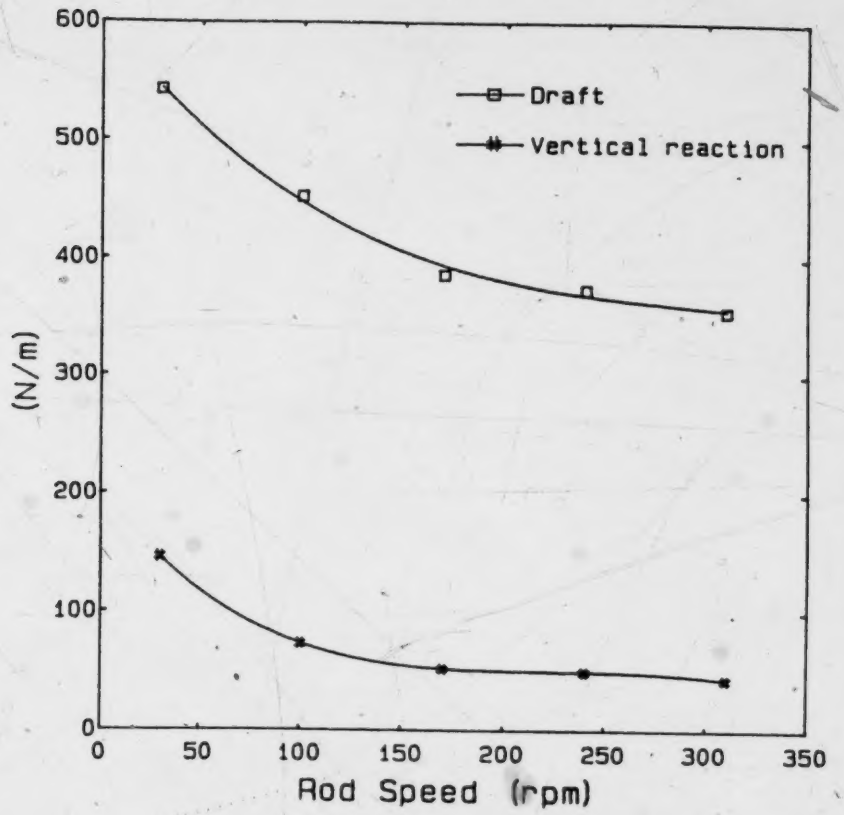

Figure 4.5 Draft and vertical reaction versus rod speed

decreased 11%. This can be explained by equation 2.2 and Figure 2.2. Soil passing over the rod likely has the same effect as an inclined plane. When the depth increases, the weight of the soil segment (G) increases and so does the area of the shear failure surface (F_1), therefore, draft (W) increases too. For the same reason, the increase in soil segment (G), soil frictional resistance (μN_1) and cohesive resistance (CF_1) will reduce the vertical reaction caused by

compacting the soil which passes under the rod. The interactions of depth with other main effects are noted in a subsequent section.

4.1.5 Main effects - travel speed

As the travel speed increased 68% from 0.39 m/s to 0.66 m/s, the draft increased 27% from 384 N/m to 460 N/m and the vertical reaction increased 29% from 64 N/m to 82 N/m. These are due to the acceleration force of soil acting on the rod.

4.2 Interaction Effects

Several significant interactions among the factors were observed. These will be discussed in the following sections.

4.2.1 Soil type-rod shape interaction for draft and vertical reaction

The interactions between the soil type and rod shape for the draft and vertical reaction are given in Figures 4.6 and 4.7. On loam soil, the triangle rod had the highest draft (604 N/m), which is 71 N/m higher than that of the fluted rod which had the lowest draft; however, on sand, the square rod had the largest draft (289 N/m) and the round rod had the lowest draft (246 N/m) (Figure 4.6). The results indicate that the effect of rod shape on draft depends on soil type. The fluted rod had the least draft on loam due to its shape and the cohesion of soil (see section 5.1.2). On cohesionless sand, the fluted rod had little advantage on

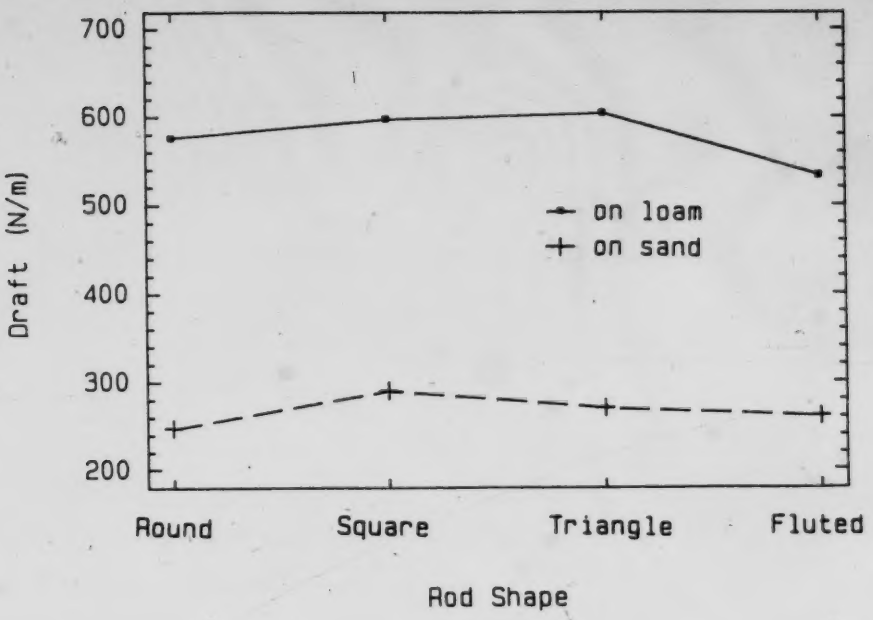

Figure 4.6 Soil type-rod shape interaction for draft

draft over the round rod which had the least effective diameter, because the draft exhibited a linear relationship with the effective diameter.

Because it had the lowest plane of separation due to its fluted shape and relatively smaller effective diameter, the fluted rod had the least vertical reaction, 126 N/m on loam (Figure 4.7). The round rod had the highest vertical reaction, 172 N/m on loam because it compacted more soil. On sand, the vertical reactions for all the rods were negative. The round rod still had the highest vertical reaction which was -2 N/m. However, the triangle rod rather than the fluted rod had the lowest vertical reaction, -16 N/m. This may be due to the three edges turning more sand over the rod.

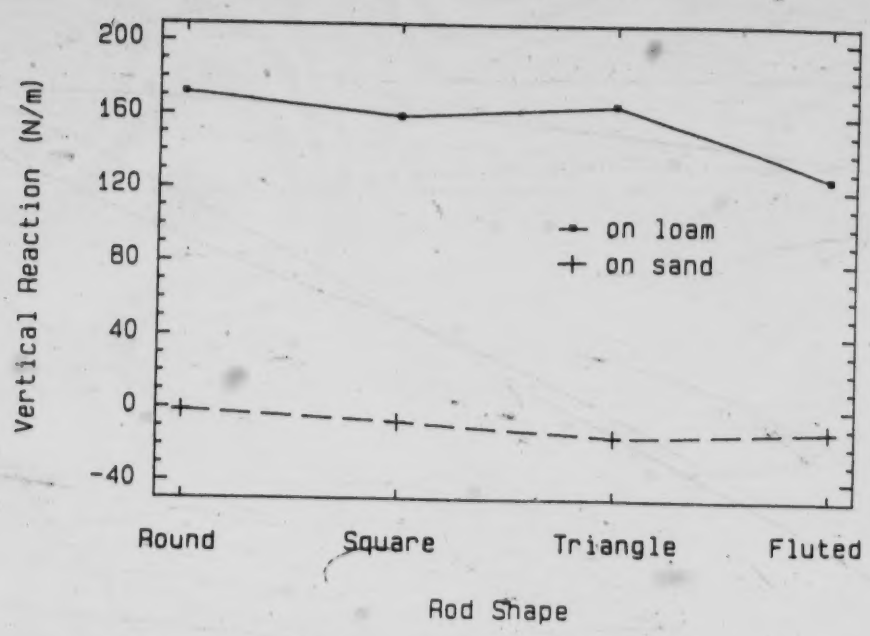

Figure 4.7 Soil type-rod shape interaction for vertical reaction

4.2.2 Soil type-rod speed for draft and vertical reaction

The soil type-rod speed interaction for the draft and vertical reaction are illustrated in Figure 4.8 and 5.9. As the rod speed increased, the draft decreased for both loam and sand. But the reductions with the rod speed were not the same. As the rod speed increased from 30 rpm to 310 rpm the draft on loam reduced 240 N/m from 730 N/m, whereas, the draft on sand reduced 136 N/m from 356 N/m.

The vertical reaction on loam decreased considerably as the rod speed increased, but the vertical reaction on sand changed very little for rod speeds greater than 100 rpm.

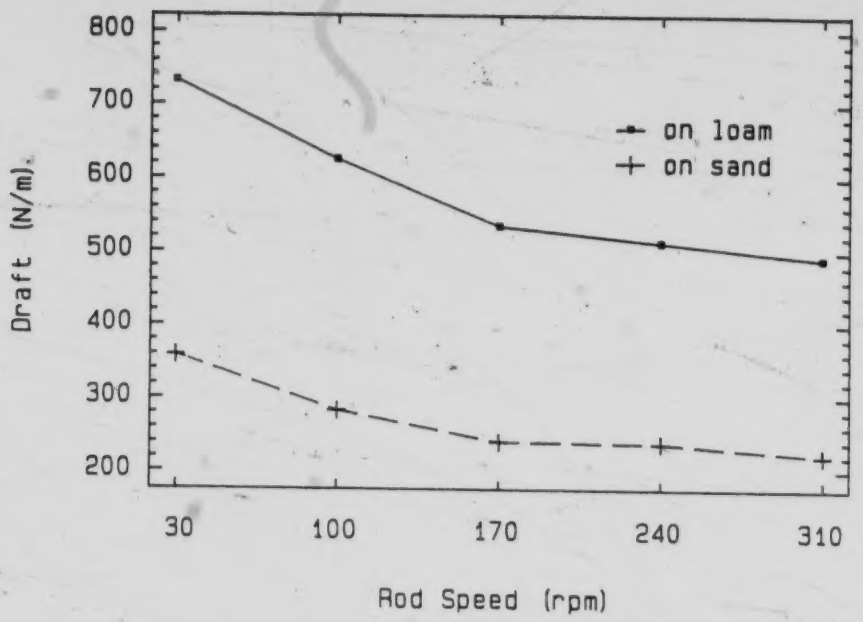

Figure 4.8 Soil type-rod speed interaction for draft

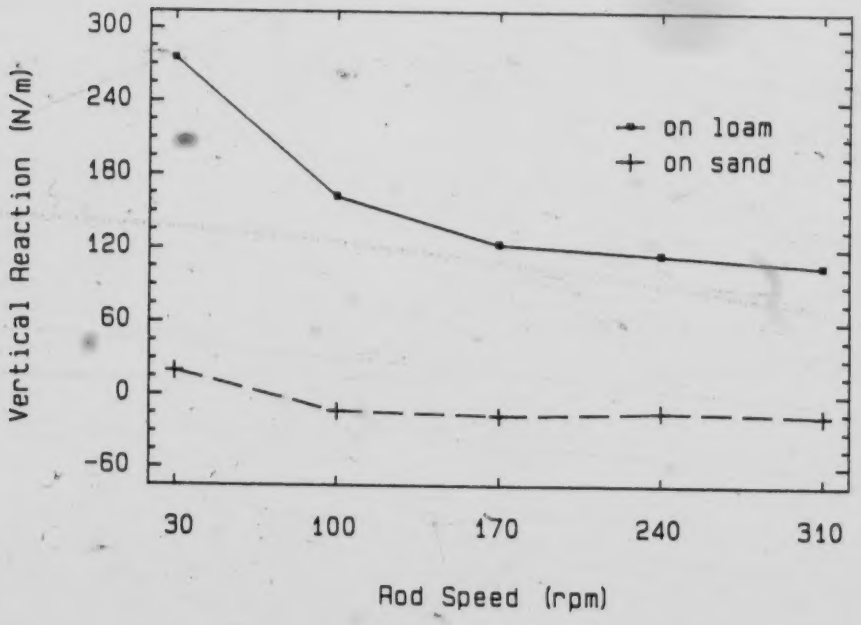

Figure 4.9 Soil type-rod speed interaction for vertical reaction

4.2.3 Rod shape-rod speed interaction for draft and vertical reaction

The interactions of rod shape and rod speed for both draft and vertical reaction are given in Figures 4.10 and 4.11. Figure 4.10 shows the relation of rod shape and rod speed for draft. As the rod speed increased, the draft for all the rods decreased, however the changes varied with different rods. The fluted rod had larger draft than the round rod at 30 rpm, however, with the increase of rod speed the draft for the fluted rod became the least. This shows that the rod speed has smaller effect on the round rod than that on the fluted rod, though the higher rod speed would generally lower the plane of separation for all the rods. The draft for the square rod and the triangle rod were closer and higher than the other two rods, because their effective diameters, 36 mm for square rod and 37 mm for triangle one, were closer and larger.

Figure 4.11 shows the relation of rod shape and rod speed for vertical reaction. As can be seen that the rod speed has different effects on different rods. At 30 rpm the vertical reactions for all the rods were very close. With an increase in rod speed, the vertical reaction for the fluted rod decreased much more than the other rods. Except for 30 rpm the round rod had the highest vertical reaction. The vertical reactions for the square rod and the triangle rod differed little. As the rod speed increased from 30 rpm to 100 rpm, the vertical reactions for the square rod and the

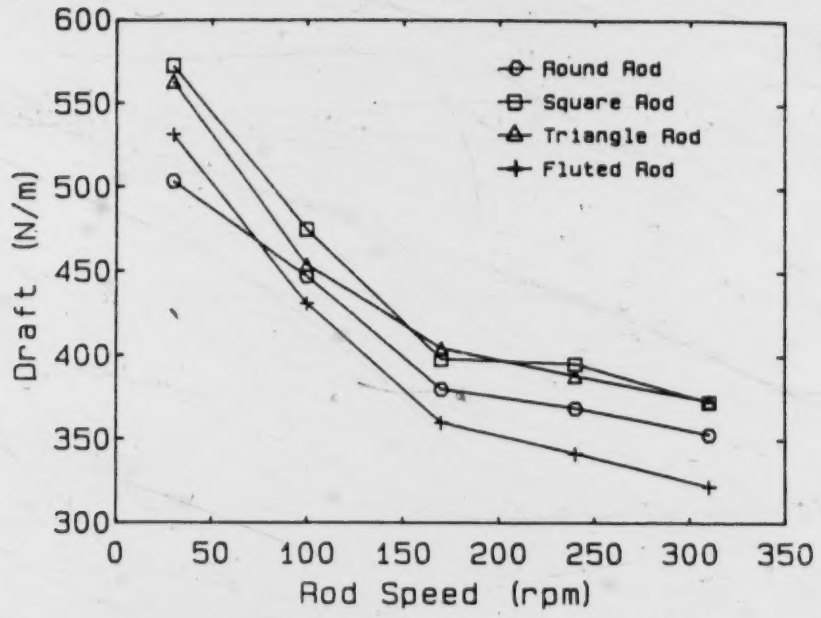

Figure 4.10 Rod shape-rod speed interaction for draft

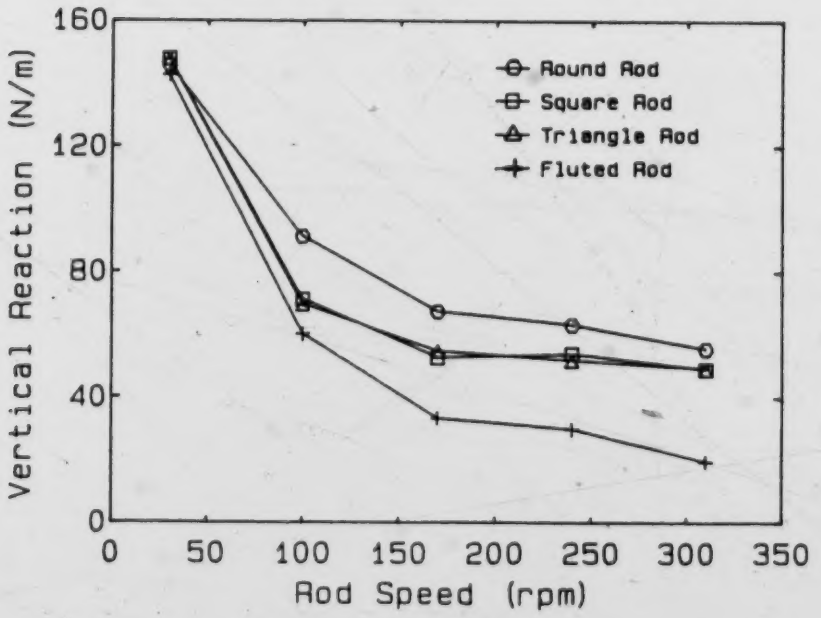

Figure 4.11 Rod shape-rod speed for vertical reaction

triangle rod decreased notably, however; after 170 rpm they decreased little.

4.2.4 Rod shape-travel speed interaction for draft and vertical reaction

The interactions of travel speed and rod shape for the draft and the vertical reaction are given in Figures 4.12 and 4.13. As the travel speed increased from 0.39 m/s to 0.66 m/s, the draft for all rods increased. However, there was a differential response depend on rod shape. At the lower travel speed the triangle rod had the largest draft, however, the square rod had the largest draft at higher travel speed. Although the fluted rod had the least draft for both travel speeds, the advantage of the fluted rod over the round rod diminished at the higher travel speed since it only had a 5.1 N/m change in draft.

The vertical reaction for all rods increased with the increase of travel speed. For both travel speeds, the round rod had the largest vertical reaction and the fluted rod had the least vertical reaction due to its lower plane of separation.

4.2.5 Rod speed-travel speed interaction for draft

The interaction of travel speed and rod speed for draft is given in Figure 4.14. There is little effect of travel speed on the draft at 30 rpm but much at 170 rpm. As the travel speed increased the benefit of using higher rod speed

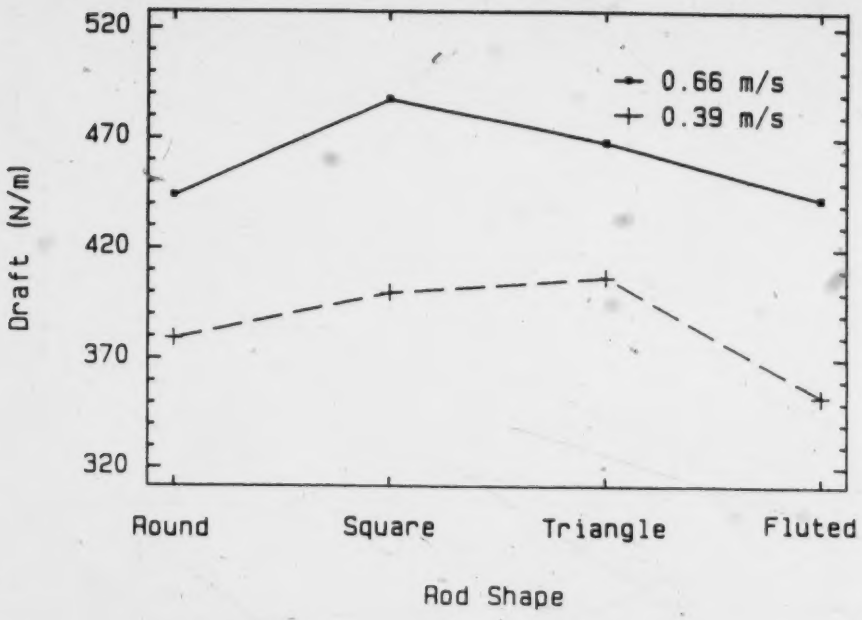

Figure 4.12 Rod shape-travel speed interaction for draft

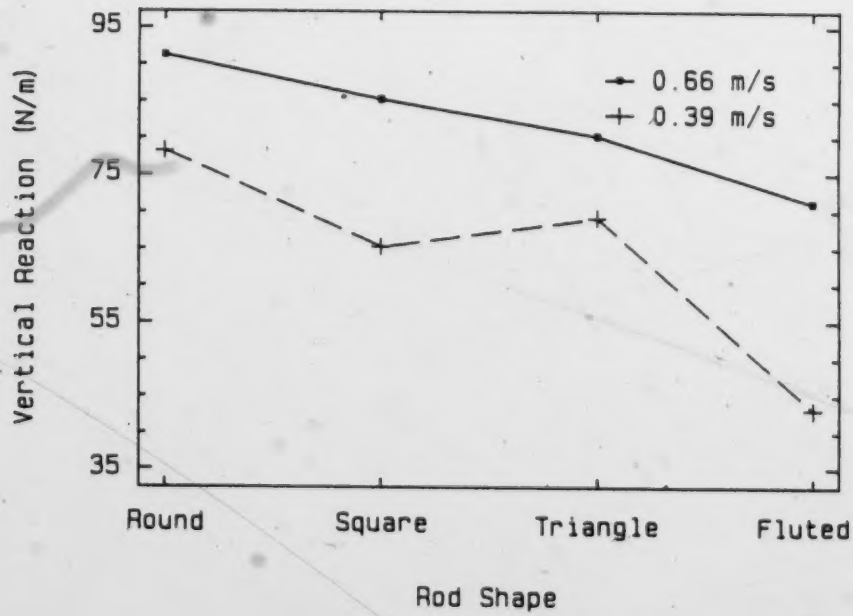

Figure 4.13 Rod shape-travel speed interaction for vertical reaction

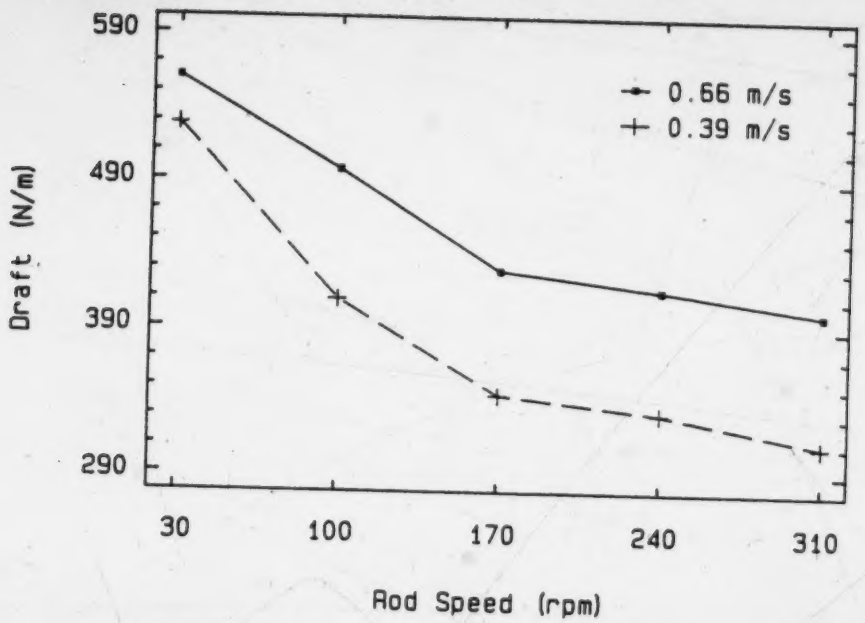

Figure 4.14 Rod speed-travel speed interaction for draft

was offset a little.

4.2.6 Rod speed-tillage depth interaction for draft

Figure 4.15 shows the relationship between tillage depth and rod speed for draft. The draft decreased 218 N/m at 8 cm depth from 608 N/m, whereas it decreased 158 N/m at 5 cm depth from 478 N/m as the rod speed increased from 30 rpm to 310 rpm.

4.2.7 Soil type-tillage depth interaction for vertical reaction

The interaction between the soil type and tillage depth for vertical reaction, which tested significant, is shown in Figure 4.16. As can be seen when the depth increased from 5

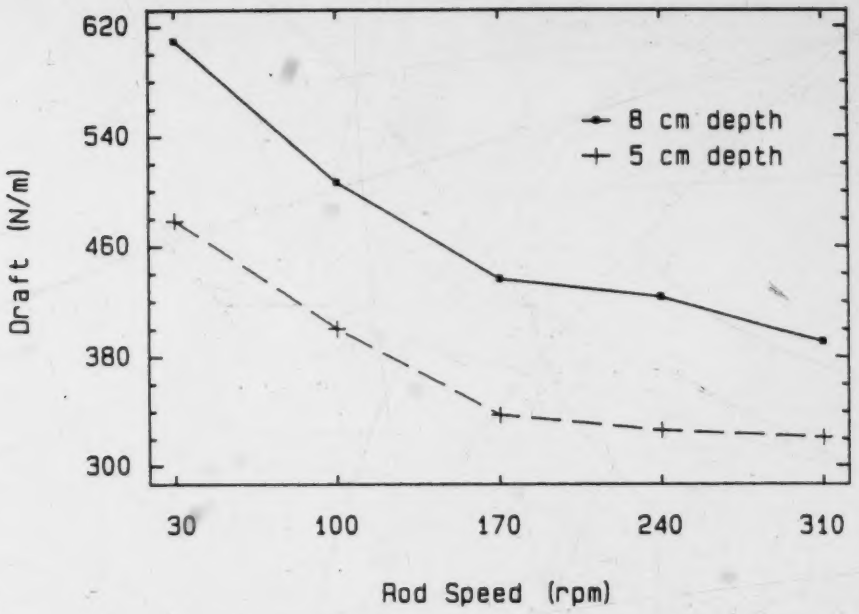

Figure 4.15 Rod speed-tillage depth interaction for draft

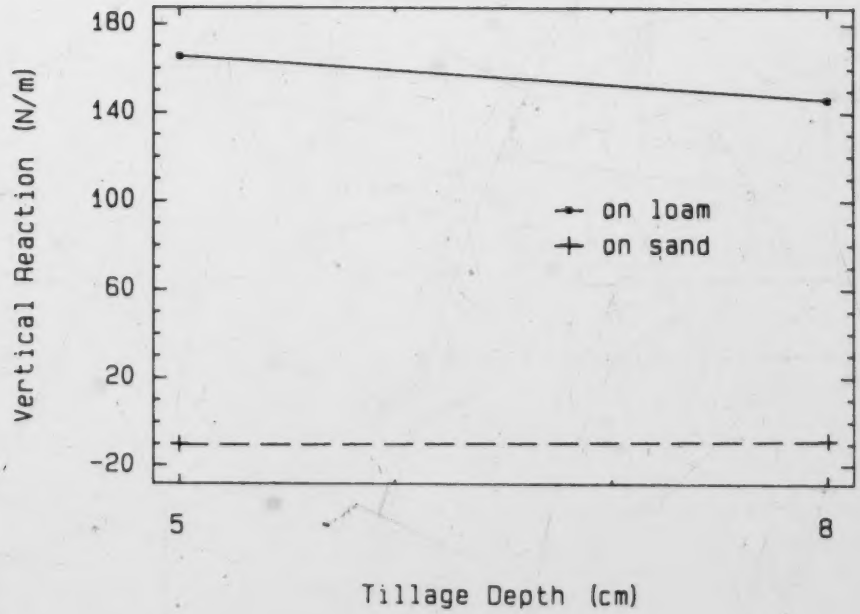

Figure 4.16 Soil type-tillage depth interaction for vertical reaction

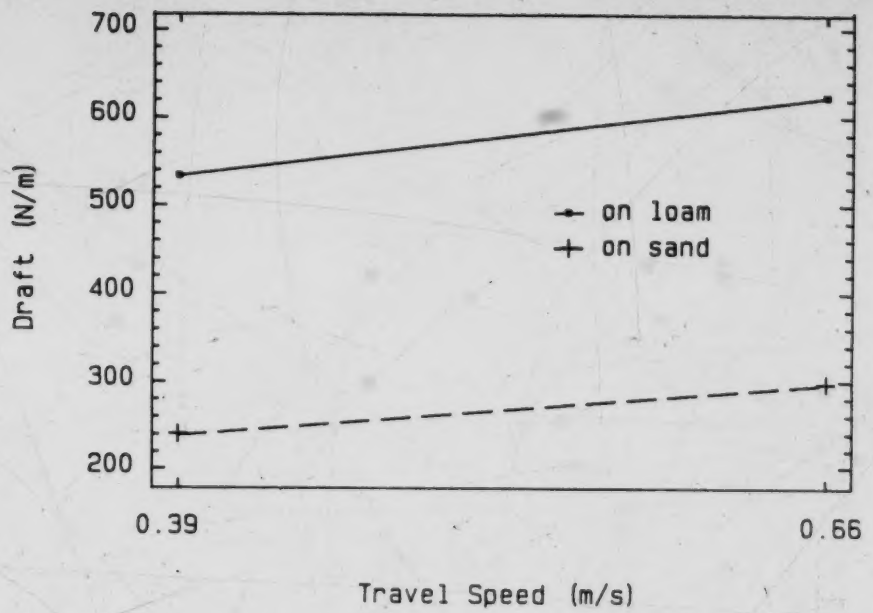

Figure 4.17 Soil type-travel speed interaction for draft

to 8 cm for the loam soil the vertical reaction reduced 19 N/m from 165 N/m to 146 N/m. But for sand, the vertical reaction only changed 2 N/m from -11 N/m to -9 N/m. The difference between the two soils could be due to the cohesive force, frictional force and the size of soil segment (G) since sand is cohesionless and has a smaller soil segment than that of loam.

4.2.8 Soil type-travel speed interaction for draft

The interaction between the soil type and travel speed for the draft is given in Figure 4.17. As the travel speed increased from 0.39 m/s to 0.66 m/s the draft for loam increased 92 N/m from 531 to 623 N/m while a 60 N/m increase from 236 N/m to 296 N/m was obtained for sand.

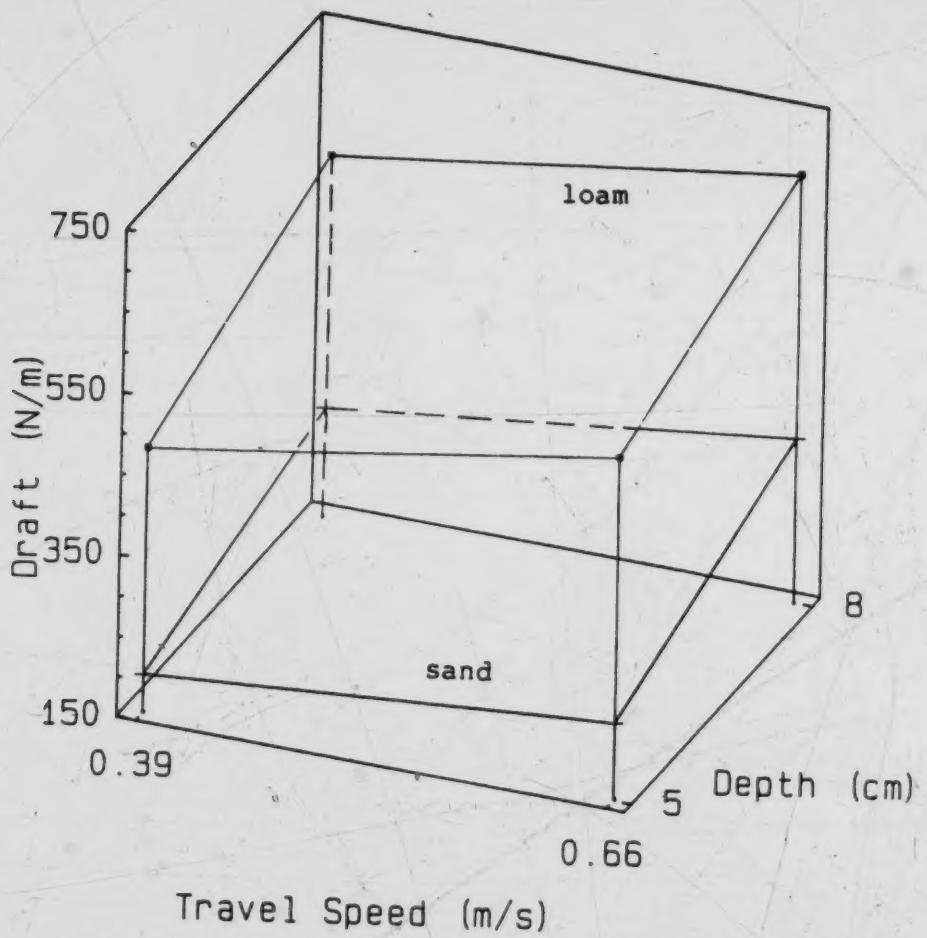

Figure 4.18 Soil type-tillage depth-travel speed interaction for draft

4.2.9 Soil type-tillage depth-travel speed interaction for draft

Soil type-tillage depth-travel speed interaction for draft is illustrated in Figure 4.18. As can be seen, draft is function of cohesion of soil, travel speed and tillage depth, which is in agreement with equation 2.2. The differential response was so small or trivial that it is not

discussed.

4.3 Power Requirement

The power required to drive and pull the rod is listed in Table 4.4. As shown the power to drive the rod is only a small portion (6%) of the total power required. The rotating power rod only changed by a few watts per meter of rod length for different soils, depths, travel speeds and rod shapes. However, as rod speed increased from 30 rpm to 310 rpm, the rotating power increased from 3 W/m to 25 W/m and this affected the total power. Figure 4.19 shows the total power and the tractive power versus the rod speed. The solid line is the best fit curve line for the total power and the dashed line is the best fit curve line for the tractive power. As rod speed increases the tractive power requirement decreases. This decrease in tractive power requirement, however, is offset by an increase in rotating power requirement. Consequently, the total power changed little after a rod speed of 170 rpm

In this study, as the rod speed increased from 170 rpm to 310 rpm the total power only reduced 5 W/m from 223 W/m to 218 W/m. If the wearing due to higher speed is taken into account, 310 rpm would be considered as the upper limit of rod speed in this case.

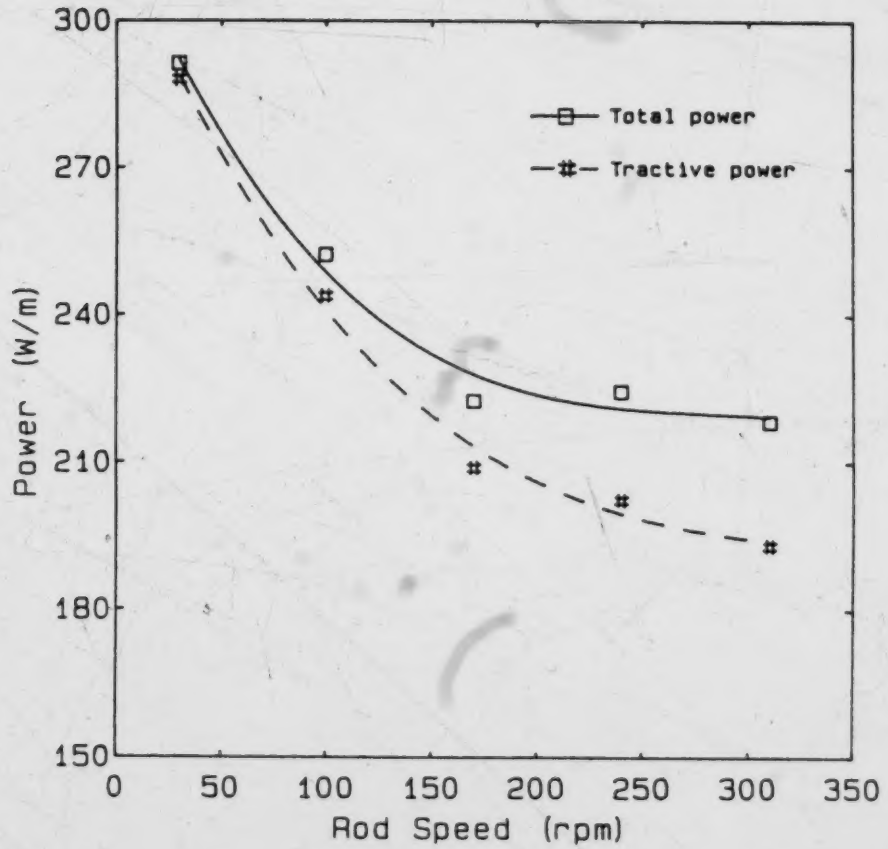

Figure 4.19 Power requirement versus rod speed

Figure 4.19 Power requirement versus rod speed

Table 4.4 MEANS OF THE MAIN EFFECTS ON POWER

Factor	Level	Tractive HP (W/m)	(%)	Rotating HP (W/m)	(%)	Total HP (W/m)
Block	1	225	95	11	5	236
	2	230	93	17	7	248
	3	226	94	15	6	241
Soil Type	Loam	310	95	16	5	326
	Sand	144	92	13	8	157
Rod Shape	Round	221	94	15	6	236
	Square	239	95	13	5	252
	Triangle	234	93	17	7	251
	Fluted	215	94	13	6	228
Rod Speed (rpm)	30	288	99	3	1	291
	100	244	97	8	3	252
	170	209	94	14	6	223
	240	202	90	22	10	224
	310	193	88	25	12	218
Depth (cm)	5	201	93	15	7	215
	8	254	95	14	5	268
Travel Speed (m/s)	0.394	151	92	13	8	164
	0.660	303	95	16	5	319
Total		227	94	15	6	242

5. CONCLUSIONS

1. The draft increased and the vertical reaction decreased for all rods as the tillage depth increased because the weight of soil segment on the rod and the area of shear failure plane increased.
2. The fluted rod had the least draft and vertical reaction of the rods because of its shape and relatively smaller effective diameter. The shape lowered the separation plane which in turn reduced the energy requirement to compact the soil passing under the rod.
3. The round rod had the largest vertical reaction because more soil passed under the round rod causing more compaction.
4. The square rod and the triangle rod had large draft due to their large effective diameters. The shapes had advantages over the round rod on vertical reactions, as they had less vertical reaction than the round rod.
5. With the increase of the rod speed, the draft and vertical reaction decreased significantly, meanwhile, the rotating power increased, offsetting the decrease in tractive power, nevertheless there was some gain in power efficiency.
6. As the travel speed increased, the draft and the vertical reaction increased.
7. The clay content in the soil affected the draft and vertical reaction. The higher the clay content, the higher the cohesion and the higher the draft and

vertical reaction.

8. The power required to rotate the rod was a small percentage of the total power required.

6. SUGGESTIONS FOR FURTHER STUDIES

Based on the results obtained in this study the following suggestions are made for further study on rod weeders:

1. A full scaled fluted rod weeder should be tested in a variety field conditions in comparison with the round rod weeder.
2. Higher travel speeds should be used to determine the relationship between the energy requirement and the travel speed.
3. Rod speed in excess of 250 rpm is not recommended because the increase in rotating power becomes appreciable.

REFERENCES

Anonymous, 1979. Canadian Grains Industry Statistical Handbook. Canadian Grains Council. Winnipeg, MB.

Atkins, R.P. 1979. Soil Reacting Forces with a Rotating Rod. Unpublished M.Sc. Thesis. Dept. of Agricultural Engineering, University of Alberta, Edmonton, AB.

Barnes, K.K. 1961. Influence of Speed on Elements of Draft of a Tillage Tool. ASAE Trans. 4:55-57. St. Joseph, MI.

Bergsteisson, J.T. 1980. Climate and Climatic Change in Western Canada. Prairie Production Symposium. Soil and Land Resources. Canadian Wheat Board.

Buckman, H.O. and N.C. Brady. 1969. The Nature and Properties of Soil. 7th Edition. The Macmillan Company / Collier-Macmillan Ltd., London.

Craig, F.C. 1980. Soil Mechanics. 2nd Edition. Van Nostrand Reinhold Company Ltd. Molly Millars Lane, Workinham, Berkshire, England

Fedorov, E.B. 1970. Some Characteristics of the Interaction of a Rod Weeder with the Soil. Chelyabinsk Institute of Mechanization of Agriculture, Soil Working Machines and Dynamic Units. Issue 56:177-188(Translation No. 865 by W.R. Gill, USDA-SEA, National Tillage Machinery Laboratory, Auburn, AL 36830, USA).

Gill, W.R. and G.E. Vanden Berg. 1967. Soil Dynamics in Tillage and Traction. U. S. Government Printing Office, Washington, D.C.

Harrison, H.P. 1980. The Rod Weeder.Agriculture & Forestry.

Vol. 3, No. 1:28-30. U. of A., Edmonton, AB.

Harrison, H.P. and R.P. Atkins. 1981. Soil Reacting Forces for a Rod Weeder from Field Measurements. ASAE Trans. 24(3):590-592, 597. St. Joseph, MI.

Holtz, R.D. and W.D. Kovace. 1981. An Introduction to Geotechnical Engineering. pp.449-455. Pretice-Hall, Inc., Englewood Cliffs, NJ.

Koolen, A. and H. Kuipers. 1983. Agricultural Soil Mechanics. Springer-Verlag. New York, NY.

Kotov, P.M. 1979. Results of Studies of the Operation of a Rod Weeder Cultivator Scientific Technichal Bullentin of the Siberian. Scientific Research Institute for Agriculture, No. 33:17-21(Translated by W.R. Gill, USDA-SEA, National Tillage Machinery Laboratory, Auburn, AL 36830, USA).

Licsko, Z.J. and H.P. Harrison. 1986. Acquisition and Processing of Soil Reaction Forces on Tillage Tools. ASAE PNR #86-106.St. Joseph, MI

Maule, C.P. 1984. Spatial Variability of Two Soil Moisture Regimes. Unpublished M.Sc. Thesis, Dept. of Soil Science, University of Alberta, Edmonton, AB. 123 pp.

McKibben, E.G. and M.O. Berry. 1952. The Value of Replication in Research. Agricultural Engineering, Vol. 33:792, 798.

Needham, J. 1984. Science and Civilization in China. Vol. 6. Pt. 2:1-40. Cambridge University Press, Cambridge, England

Pelton, W.L. 1980. Tillage for Cereal Crop Production. Prairie Production Symposium. Soil and Land Resources. Canadian Wheat Board.

Procedures for Testing Soils, 1964. American Society for Testing and Material, Baltimore, USA

Rowe, R.J. 1959. Effects of Speed on the Elements of Draft of a Simple Tillage Tool. M.S. Thesis, Iowa State University, IA. 94 pp., illus.

Sohne, I.W. 1956. Some Basic Considerations of Soil Mechanics as Applied to Agricultural Engineering. Grundlagen der Landtechnik 7: 11-27. Natl. Engin. Eng. Translation 53.

Steel, R.G.O. and J.H. Torrie. 1980. Principles and Procedures of Statistics. McGraw-Hill.

Vervein, K.K. and G.Z. Gaifullin. 1979. Study of Soil Sticking and the Expenditure of Power to Drive Rod Weeder Tools. Problems of Mechanization of Agricultural Production of Kazakhstan, Alma-Ata, 90-99 pp. (Translated by W.R. Gill, USDA-SEA, National Tillage Machinery Laboratory, Auburn, AL 36830, USA).

APPENDIX A: FACTORS AND THIRE SYMBOLS

Table A. FACTORS AND THIRE SYMBOLS

Factor	Symbols	Level
Soil Type	T1	Loam
	T2	Sand
Rod Shape	S1	Round
	S2	Square
	S3	Triangle
	S4	Fluted
Travel Speed	V1	0.39 m/s
	V2	0.66 m/s
Rod Speed	R1	30 rpm
	R2	100 rpm
	R3	170 rpm
	R4	240 rpm
	R5	310 rpm
Depth	D1	50 mm
	D2	80 mm

APPENDIX B: DRAFT

Table B.1 DRAFT (N/m) - BLOCK 1

T	D	V	S	R1	R2	R3	R4	R5
			S1	621.0	455.2	371.7	447.2	453.6
		V1	S2	632.3	524.1	398.6	373.1	388.8
			S3	878.8	591.2	407.8	529.9	690.1
	D1		S4	499.4	472.2	367.7	349.4	356.7
			S1	620.6	588.2	477.3	566.9	572.8
		V2	S2	686.5	688.7	610.7	529.1	477.8
			S3	673.6	595.9	524.6	643.3	662.3
T1			S4	660.9	528.8	457.7	448.3	422.1
			S1	932.1	702.6	610.7	576.6	495.0
		V1	S2	777.6	650.5	525.5	492.9	484.0
			S3	912.3	620.7	711.8	533.9	475.3
	D2		S4	818.7	608.2	493.2	466.7	447.6
			S1	665.2	719.7	626.3	666.5	620.1
		V2	S2	721.5	713.0	638.4	604.1	557.4
			S3	856.0	661.4	619.3	620.3	574.1
			S4	785.1	693.3	635.2	568.5	546.0
			S1	233.7	175.6	163.2	161.1	154.9
		V1	S2	306.9	209.4	177.1	181.7	175.4
			S3	277.4	187.2	162.6	169.1	157.7
	D1		S4	266.1	205.5	166.6	137.5	128.1
			S1	255.4	237.0	203.4	196.1	183.4
		V2	S2	335.2	276.4	227.8	236.6	229.3
			S3	304.8	247.3	221.0	224.9	214.0
T2			S4	311.9	257.7	230.3	207.1	186.6
			S1	328.0	259.5	226.1	217.4	190.5
		V1	S2	395.5	288.6	225.7	290.7	227.4
			S3	378.9	275.5	229.9	221.2	193.0
	D2		S4	365.1	247.6	207.4	259.0	173.8
			S1	347.7	316.5	285.8	280.5	254.1
		V2	S2	440.6	376.0	326.2	317.3	316.2
			S3	406.2	365.5	312.9	300.3	267.6
			S4	404.2	341.1	281.7	341.2	277.8

Table B.2 DRAFT (N/m) - BLOCK 2

T	D	V	S	R1	R2	R3	R4	R5
			S1	569.4	550.6	430.3	389.7	254.8
		V1	S2	803.8	498.6	383.9	443.9	396.1
			S3	605.8	482.7	477.3	467.7	350.9
			S4	566.3	533.6	458.0	311.4	371.1
	D1							
			S1	610.4	600.6	538.2	494.3	513.4
		V2	S2	817.5	696.6	632.3	533.9	530.6
			S3	704.0	646.3	568.6	456.9	461.8
			S4	601.9	662.4	472.6	457.2	467.3
T1								
			S1	793.4	659.0	549.3	490.9	454.4
		V1	S2	857.2	680.6	517.7	546.8	516.3
			S3	781.0	662.3	553.0	504.6	529.7
			S4	745.6	618.9	482.0	525.2	449.9
	D2							
			S1	825.3	784.9	637.9	662.1	616.7
		V2	S2	892.3	795.0	746.9	715.2	640.2
			S3	890.4	802.5	640.1	657.9	534.7
			S4	839.4	696.7	629.8	590.1	558.6
			S1	247.1	187.6	162.7	146.4	155.4
		V1	S2	294.1	216.3	188.2	182.5	156.6
			S3	279.4	200.8	169.8	168.3	160.0
			S4	285.7	200.4	164.2	156.9	126.8
	D1							
			S1	260.0	241.9	199.6	195.0	184.1
		V2	S2	354.3	284.3	232.3	241.2	220.6
			S3	296.3	258.1	223.8	213.6	196.4
			S4	[illegible].5	250.3	220.7	219.3	199.2
T2								
			S1	365.7	270.4	241.2	241.8	227.3
		V1	S2	446.9	308.6	266.7	253.2	248.3
			S3	411.4	294.7	256.8	242.6	233.8
			S4	429.8	290	234.1	213.5	206.2
	D2							
			S1	397.4	352.7	302.0	288.8	276.6
		V2	S2	494.1	417.2	347.2	346.2	333.1
			S3	454.0	405.6	348.0	316.4	285.7
			S4	480.9	378.3	323.1	325.4	302.4

Table B.3 DRAFT (N/m) - BLOCK 3

T	D	V	S	R1	R2	R3	R4	R5
			S1	615.5	680.1	440.4	386.0	414.2
		V1	S2	643.4	497.3	437.6	409.4	371.9
			S3	661.7	509.1	509.2	422.4	383.0
	D1		S4	636.3	415.8	319.3	316.6	285.7
			S1	729.5	592.5	539.2	491.9	569.9
		V2	S2	703.2	621.5	507.6	548.3	566.4
			S3	703.0	660.1	596.6	483.9	555.8
T1			S4	644.5	543.5	465.7	458.4	455.0
			S1	627.0	597.2	525.4	481.0	429.8
		V1	S2	715.6	653.2	547.2	582.2	496.5
			S3	749.5	572.5	549.5	545.3	477.1
	D2		S4	702.0	499.6	459.6	407.3	385.2
			S1	741.1	673.1	629.3	559.8	551.1
		V2	S2	832.7	764.6	594.8	596.3	587.9
			S3	781.5	689.4	634.5	609.7	601.2
			S4	892.2	761.7	619.2	549.5	520.7
			S1	252.6	193.9	172.8	170.4	177.9
		V1	S2	316.1	217.6	168.8	194.6	178.8
			S3	294.7	209.2	187.0	181.6	175.0
	D1		S4	286.5	193.6	168.2	137.3	133.0
			S1	275.7	246.0	230.4	216.7	220.7
		V2	S2	339.7	282.1	240.2	247.3	247.9
			S3	319.7	264.6	215.8	225.9	209.3
T2			S4	322.5	258.0	224.0	221.8	204.9
			S1	370.6	286.1	239.4	229.2	223.0
		V1	S2	448.9	327.6	257.7	266.2	260.4
			S3	435.5	292.1	252.9	249.6	241.8
	D2		S4	429.3	297.3	232.7	211.9	212.3
			S1	399.5	358.9	315.2	287.9	275.0
		V2	S2	488.7	414.3	350.3	348.7	325.5
			S3	460.0	399.5	333.0	319.0	316.4
			S4	466.9	381.9	322.7	311.4	303.4

APPENDIX C: VERTICAL REACTION

Table C.1 VERTICAL REACTION (N/m) - BLOCK 1

T	D	V	S	R1	R2	R3	R4	R5
			S1	273.4	147.9	120.9	134.1	127.2
		V1	S2	248.6	151.6	113.5	103.8	115.0
			S3	361.9	156.9	106.9	156.5	199.5
			S4	193.8	110.8	94.0	40.6	58.0
	D1							
			S1	266.4	198.9	129.8	168.8	128.9
		V2	S2	289.9	191.5	164.4	133.1	107.8
			S3	284.7	171.7	115.7	177.6	165.4
			S4	289.3	153.2	94.9	138.9	49.7
T1								
			S1	317.2	166.4	139.9	135.8	112.6
		V1	S2	244.1	140.1	105.6	77.8	87.0
			S3	285.3	114.6	115.0	84.4	97.8
			S4	277.8	110.1	58.6	39.7	43.3
	D2							
			S1	180.4	160.7	113.7	191.6	134.2
		V2	S2	223.4	137.9	107.0	97.2	89.1
			S3	279.0	126.5	96.8	82.8	104.9
			S4	270.8	144.6	105.3	148.7	54.4
			S1	8.8	-11.6	-15.3	-19.9	-20.8
		V1	S2	-0.7	-21.8	-18.8	-16.2	-22.2
			S3	-1.3	-26.1	-22.4	-27.3	-33.6
			S4	11.4	-26.7	-28.7	-28.2	-28.3
	D1							
			S1	29.0	2.4	-3.5	-11.6	-12.7
		V2	S2	30.7	-6.7	-12.6	-15.8	-10.6
			S3	19.7	-11.0	-13.1	-10.0	-28.6
			S4	29.3	3.1	-16.8	-18.7	-22.1
T2								
			S1	16.1	-6.1	-4.4	-7.9	-10.3
		V1	S2	14.3	-29.7	-29.0	-8.1	-17.8
			S3	8.5	-28.8	-38.1	-23.9	-23.4
			S4	8.8	-26.8	-21.1	-7.4	-37.5
	D2							
			S1	31.6	9.0	5.4	5.1	-0.8
		V2	S2	35.4	-8.2	-14.5	-4.2	5.5
			S3	36.7	-15.4	-26.7	-4.4	-13.1
			S4	41.1	0.7	-11.8	5.6	-25.7

Table C.2 VERTICAL REACTION (N/m) - BLOCK 2

T	D	V	S	R1	R2	R3	R4	R5
			S1	242.1	177.9	130.5	90.6	85.2
		V1	S2	300.8	144.4	79.3	122.4	91.8
			S3	217.6	138.5	118.2	127.9	93.1
			S4	221.8	122.7	121.3	61.4	63.2
	D1							
			S1	265.7	201.8	141.5	108.0	115.7
		V2	S2	347.7	193.2	170.0	123.7	114.1
			S3	275.5	199.3	166.9	106.5	125.1
			S4	244.8	202.7	100.2	96.8	110.7
T1								
			S1	307.1	147.7	136.3	105.4	91.9
		V1	S2	283.2	153.8	93.3	123.2	90.8
			S3	249.8	148.8	122.3	101.3	124.1
			S4	227.0	114.1	78.3	80.8	61.8
	D2							
			S1	287.5	203.2	148.2	146.5	127.0
		V2	S2	304.9	161.2	161.9	143.3	119.3
			S3	314.1	185.1	112.8	143.0	69.0
			S4	285.1	150.2	97.7	78.5	69.3
			S1	7.7	-9.5	-10	-11.2	-17.7
		V1	S2	-7.2	-27.9	-34.0	-13.3	-24.4
			S3	-5.8	-29.1	-28.4	-33.3	-30.7
			S4	-6.7	-33.2	-31.5	-27.3	-29.8
	D1							
			S1	31.0	6.7	-1.1	-6.4	-11.6
		V2	S2	24.8	-10.9	-14.4	-3.3	-7.9
			S3	19.4	-15.5	-17.4	-20.3	-21.3
			S4	24.4	-10.9	-22.5	-12.6	-13.7
T2								
			S1	5.0	-21.4	-20.4	-17.0	-18.4
		V1	S2	2.4	-28.7	-19.8	-18.4	-11.2
			S3	-2.8	-32.8	-26.2	-23.3	-27.4
			S4	17.7	-22.7	-28.6	-35.5	-22.5
	D2							
			S1	32.3	-7.4	-11.0	-7.5	-13.8
		V2	S2	43.1	-7.2	-11	0.3	-3.4
			S3	22.6	-16.2	-21.8	-13.3	-18.7
			S4	50.4	6.4	-15.2	-9.4	-8.7

Table C.3 VERTICAL REACTION (N/m) - BLOCK 3

T	D	V	S	R1	R2	R3	R4	R5
			S1	272.0	279.2	148.8	154.1	148.6
		V1	S2	275.4	148.4	140.6	121.2	104.8
			S3	298.6	213.4	177.0	143.9	123.9
			S4	300.8	110.7	69.0	59.7	55.7
	D1							
			S1	343.1	207.6	187.4	157.5	192.4
		V2	S2	318.2	191.9	131.8	139.5	159.5
			S3	325.7	212.1	189.6	118.7	164.7
			S4	298.4	174.1	105.2	103.6	86.4
T1								
			S1	212.8	166.1	145.2	118.5	102.5
		V1	S2	218.7	168.0	136.0	111.1	116.0
			S3	242.2	119.3	149.6	132.7	101.3
			S4	216.5	70.4	64.0	46.4	40.2
	D2							
			S1	272.8	178.5	149.9	116.4	124.2
		V2	S2	271.2	159.8	105.8	112.3	109.4
			S3	271.6	144.0	131.0	113.5	110.2
			S4	334.4	156.0	85.2	61.5	54.5
			S1	18.6	-4.2	-2.9	-7.1	-11.1
		V1	S2	-0.2	-29.3	-29.5	-11.8	-15.3
			S3	-8.8	-27.5	-31.7	-33.5	-36.2
			S4	5.8	-29.8	-22.9	-34.4	-32.3
	D1							
			S1	39.6	9.7	8.0	-2.8	-4.0
		V2	S2	25.4	-9.3	-17.9	-8.6	-9.0
			S3	18.0	-14.5	-18.8	-22.0	-26.2
			S4	34.0	-1.7	-17.0	-20.2	-21.9
T2								
			S1	5.5	-17.3	-14.3	-18.7	-22.2
		V1	S2	13.9	-48.2	-30.8	-14.6	-10.6
			S3	3.0	-33.8	-31.2	-24.6	-27.3
			S4	3.4	-32.4	-36.0	-35.0	-26.3
	D2							
			S1	29.4	-0.8	-7.1	-10.5	-16.9
		V2	S2	35.9	-8.4	-13.6	-1.9	-2.5
			S3	27.0	-11.9	-13.1	-13.4	-13.7
			S4	37.9	-3.7	-22.7	-19.7	-12.5

APPENDIX D: TORQUE

Table D.1 TORQUE (Nm/m) - BLOCK 1

T	D	V	S	R1	R2	R3	R4	R5
			S1	8.0	5.4	5.1	10.5	4.1
		V1	S2	3.7	3.5	7.6	0.4	1.8
			S3	11.2	4.9	4.7	9.3	12.5
			S4	5.8	4.7	5.4	8.0	5.2
	D1							
			S1	7.1	5.8	4.7	7.8	6.7
		V2	S2	5.0	3.5	4.4	2.3	0.6
			S3	6.2	4.2	4.2	9.1	14.4
			S4	8.3	5.5	4.0	7.9	4.6
T1								
			S1	1.3	-0.5	0.1	5.6	4.3
		V1	S2	1.9	3.4	3.5	-1.1	4.4
			S3	11.4	3.5	7.0	5.9	-0.1
			S4	-2.6	-4.0	-1.9	2.2	3.9
	D2							
			S1	-3.5	-2.6	-2.6	4.0	4.7
		V2	S2	1.6	-0.3	5.5	2.9	-1.6
			S3	9.7	2.4	3.5	3.7	-1.2
			S4	4.8	-4.5	-4.4	3.6	8.4
			S1	3.9	6.8	9.1	3.8	3.4
		V1	S2	5.7	3.4	2.5	9.2	4.4
			S3	5.6	2.6	2.7	1.4	0.1
			S4	0.0	-3.3	-4.1	4.3	3.8
	D1							
			S1	4.7	4.1	3.2	5.3	4.8
		V2	S2	6.8	7.0	4.0	8.1	5.9
			S3	8.8	4.7	4.3	9.9	3.8
			S4	-0.0	3.4	-2.3	11.9	6.3
T2								
			S1	0.7	0.0	0.0	1.6	0.7
		V1	S2	7.8	6.5	5.3	3.4	1.8
			S3	7.5	2.9	-1.3	0.4	1.4
			S4	3.3	5.9	0.0	5.4	2.7
	D2							
			S1	1.6	3.4	1.0	3.2	2.5
		V2	S2	9.0	7.7	7.6	3.5	9.3
			S3	3.8	7.1	0.7	2.5	1.7
			S4	4.4	6.5	0.9	6.5	5.4

Table D.2 TORQUE (Nm/m) - BLOCK 2

T	D	V	S	R1	R2	R3	R4	R5
			S1	9.1	8.9	7.3	12.8	3.9
		V1	S2	10.8	6.7	6.3	5.0	3.1
			S3	2.6	1.6	4.8	4.3	8.4
			S4	10.7	8.1	10.1	1.2	3.4
	D1							
			S1	9.6	9.2	8.3	7.6	9.8
		V2	S2	11.9	8.8	9.8	8.9	8.1
			S3	2.4	2.0	3.2	3.9	4.7
			S4	10.3	10.7	7.1	3.7	3.2
T1								
			S1	5.9	-0.6	-0.8	6.6	12.1
		V1	S2	2.4	1.3	2.4	4.8	3.2
			S3	0.4	0.2	-0.0	2.6	4.0
			S4	8.2	6.1	5.7	4.2	3.7
	D2							
			S1	1.3	-0.6	2.8	12.7	8.3
		V2	S2	3.4	-1.0	1.3	3.7	3.0
			S3	2.6	5.1	6.2	8.5	8.6
			S4	10.0	11.2	6.0	3.9	3.4
			S1	4.4	1.7	1.0	5.7	6.3
		V1	S2	13.5	6.9	6.0	-1.0	1.7
			S3	8.6	6.7	10.6	6.2	5.6
			S4	7.7	5.4	4.7	-1.1	3.8
	D1							
			S1	3.8	3.7	7.0	7.4	7.0
		V2	S2	10.6	8.5	7.0	1.2	0.7
			S3	9.6	13.1	7.7	7.7	7.6
			S4	8.9	7.5	11.6	1.6	1.1
T2								
			S1	12.5	14.8	8.7	7.1	6.0
		V1	S2	11.9	7.3	6.7	6.6	2.8
			S3	10.1	7.4	7.7	6.7	6.3
			S4	9.9	6.3	4.3	4.3	3.4
	D2							
			S1	13.7	11.7	10.6	12.7	7.4
		V2	S2	12.6	10.8	14.2	5.9	5.5
			S3	16.4	9.8	8.5	8.4	13.0
			S4	11.6	9.1	7.6	7.4	6.7

Table D.3 TORQUE (Nm/m) - BLOCK 3

T	D	V	S	R1	R2	R3	R4	R5
			S1	6.9	9.7	10.4	3.0	3.4
		V1	S2	10.6	7.3	4.0	6.4	5.7
			S3	7.6	7.0	9.2	8.3	7.4
			S4	6.3	5.4	1.5	5.3	4.3
	D1							
			S1	9.2	5.8	4.8	3.2	7.5
		V2	S2	6.5	3.5	3.0	7.9	9.2
			S3	7.6	6.0	11.7	12.0	9.6
			S4	6.6	3.7	3.0	12.5	6.5
T1								
			S1	1.2	2.1	2.2	8.1	7.5
		V1	S2	6.8	7.5	8.1	13.5	4.1
			S3	6.1	5.5	12.6	16.1	9.8
			S4	10	7.9	4.0	7.5	6.9
	D2							
			S1	3.0	0.8	1.6	12.5	8
		V2	S2	7.4	7	10.1	3.1	3.9
			S3	10.0	3.9	5.1	10.0	9.8
			S4	7.7	4.3	3.9	8.1	7.3
			S1	2.7	1.4	0.8	-0.4	0.0
		V1	S2	2.2	2.0	6.6	2.2	-3.0
			S3	3.0	2.3	7.5	3.7	3.1
			S4	3.9	8.9	0.8	7.5	3.0
	D1							
			S1	4.0	3	3.6	1.2	0.8
		V2	S2	2.6	3.0	2.7	2.3	-1.1
			S3	3.3	7.2	7.0	5.3	4.8
			S4	5	3.6	2.4	5.7	5.2
T2								
			S1	4.8	3.5	7.8	5.3	2.9
		V1	S2	3.7	2.9	4.4	2.6	7.9
			S3	7.2	9.8	9.1	-0.2	-0.4
			S4	6.1	4.1	3.3	0.0	0.5
	D2							
			S1	7.0	4.4	4.0	3.8	3.9
		V2	S2	4.8	3.9	3.6	4.0	9.2
			S3	7.5	6.4	5.7	0.5	8.7
			S4	6.9	11.5	5.0	2.7	2.9